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SOME PHYSICAL FACTORS AFFECTING RADIOGRAPHIC IMAGE QUALITY: THEIR THEORETICAL BASIS AND MEASUREMENT

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Lloyd M. Bates, Sc.D.

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ABSTRACT

report

This project carried out under contract between The Johns Hopkins University and the Bureau of Radiological Health, Public Health Service, reviews the medical diagnostic process involved in determining the pathological condition of a patient made on the basis of available roentgenological information. In diagnostic roentgenology, information relating to the patient is made available through the medium of x rays and is displayed in the form of a visual image. The final step in information acquisition is the detection and recognition by the roentgenologist of patterns in the image.

Several years ago, a program of work on the physics of diagnostic roentgenology was established at the Johns Hopkins University. The general purpose of this program was threefold: (1) to carry out a fundamental study of the parameters of an imaging system that affect image quality; (2) to devise methods to measure these parameters; and (3) to make available to the field of radiology the results of these measurements on apparatus currently available in the United States.

The manner in which the measurements were analyzed and a summary of the characteristics of radiographic films and screens currently available in the United States are included. Detailed data from the measurements are not included because of their bulk; these data will be published as a separate report in the Environmental Health Series. A set of tables and curves are presented in the appendix of this report to indicate the format in which the data will be published.

Representative products and manufacturers are named for identification only, and listing does not imply endorsement by the Public Health Service and the U.S. Department of Health, Education, and Welfare.

SOME PHYSICAL FACTORS AFFECTING RADIOGRAPHIC IMAGE QUALITY: THEIR THEORETICAL BASIS AND MEASUREMENT

CHAPTER I. INTRODUCTION

The medical diagnostic process involves a decision regarding the pathological condition of a patient made on the basis of available information. In diagnostic roentgenology, information relating to the patient is made available through the medium of x rays and is displayed in the form of a visible image.

INFORMATIONAL CONTENT AND IMAGE QUALITY

The final step in information acquisition is the detection and recognition by the roentgenologist of patterns in the image. This aspect of diagnostic roentgenology is therefore partly subjective in nature; however, the image has a finite informational content representing the upper limit of information which can be acquired from it, regardless of whether this acquisition is carried out subjectively or otherwise. The informational content is governed by factors purely physical in nature; hence the effect of these factors on informational content is amenable to objective investigation and measurement.

There is as yet no single quantitative definition of the informational content of a roentgenographic image; therefore, the less specific term "image quality" is commonly used as an expression of the relative informational content.

Image quality is determined by a complex interplay of several properties of the image: density, contrast, unsharpness, and resolution. These properties, for which quantitative definitions exist, are discussed in the section entitled "Radiological Optics."

The properties of the image that determine image quality are governed by physical factors associated with several stages of the imaging process: x-ray production, x-ray image formation, and visible image formation. Those factors associated with the final stage of the imaging process — the characteristics of the photoreceptors that transform the x-ray image into a visible image — are discussed herein. The interrelationship of photoreceptors with the other stages of the imaging process is presented below, and following sections will discuss and define the properties of the visible image. Some relevant interrelationships between the x-ray image and the visible image are also considered.

THE IMAGING PROCESS

The production of a roentgenographic image may be considered as a process involving three distinct stages: the generation of an appropriate x-ray beam, the production of an "x-ray image" when the beam is transmitted through the patient, and the transformation of the x-ray image into a visible roentgenographic image.

THE X-RAY BEAM

The beam of radiation emerging from the x-ray generator consists of a stream of photons, the individual energies of which are distributed over a range determined by the electrical potential across the x-ray tube and the quantity of matter through which the beam has passed on its emergence from the tube. The material through which the beam normally passes consists of the glass wall of the x-ray tube and "filters" that may have been purposely added to modify the photon energy distribution. The total number of photons comprising the energy distribution is a function of the total number of electrons which were transferred across the tube during the x-ray production process. The rate at which photons emerge from the tube is linearly dependent on the rate of electron flow across the tube.

Two properties of the x-ray beam, which affect image quality, are referred to in general terms as the quantity and quality of the radiation. These properties are related to the total number of photons comprising the beam and the energy distribution of the individual photons.

Quantity refers to the radiant energy per unit area which is carried to a point in space by the x-ray beam. Radiant energy is the sum of the energies of the individual photons. When an object has had a quantity of radiation incident on it, it is said to have been exposed or to have received an exposure. The international unit of exposure is the roentgen (1). The roentgen may be described as that quantity of x radiation which, through ionization of air, releases a unit quantity of charge per unit volume of air. It follows that the time rate of change of exposure is the definition of exposure rate.

The roentgen does not in itself specify the energy deposited in an irradiated object, nor does it directly specify the energy incident on the object; however, for an x-ray beam of a given photon energy distribution, both the energy incident on and the energy deposited in a given object is linearly proportional to the exposure in roentgens.

The photon energy distribution, or energy spectrum of the x-ray beam, is a fundamental property of the beam and is generally termed "beam quality." If the beam quality is specified completely, the entire energy spectrum must be determined. This can be done through a rather complicated laboratory procedure but is unnecessary for most practical purposes. The fractional number of incident photons, which penetrate a given thickness of matter, is a direct function of the photon energy; therefore an x-ray beam with a photon energy distribution whose "average" energy is high will be more penetrating than one with a lower "average" photon energy. A measure of the degree to which x-ray beams penetrate matter provides a unit usually adequate to compare beam qualities. The quality of an x-ray beam is therefore expressed as its half-value-layer. The half-value-layer is defined as that thickness of material necessary to reduce the exposure rate to one-half its initial value. The normal range of beam quality used in diagnostic roentgenology extends from about 2-mm Al to 6-mm Al.

Examination of a plane transverse to the x-ray beam incident on a patient shows a relatively even distribution of exposure rates across this plane, and the quality of the beam passing through any given area is representative of the beam as a whole.

THE X-RAY IMAGE

Different tissues of the body and different thicknesses of tissue absorb different fractions of the number of photons incident on them; consequently, after the x-ray beam has passed through these tissues, there is a variation in exposure rate across a plane transverse to the x-ray beam. The magnitude of these variations and the relative positions on the plane at which these changes in exposure rate occur are the mechanisms by which x rays transfer information to the observer. The pattern of x-ray intensities is called the x-ray image.

The absorption of x rays by various tissues of the body is dependent on the atomic composition of these tissues as well as the half-value-layer of the radiation. For a given half-value-layer, tissues containing a large fraction of high atomic number elements will absorb a greater fraction of the incident radiation than tissues of equal thickness having a lower fraction of high atomic number elements. The magnitude of the difference in absorption by two tissues of different atomic composition is a function of the half-value-layer of the x-ray beam. In the diagnostic range of beam quality, a beam of low half-value-layer will undergo a greater differential absorption than one of high half-value-layer. For this reason, a low half-value-layer beam will produce a more pronounced x-ray image; that is, one in which the exposure variations across the beam are greater.

The upper limit to the improvement in x-ray image quality effected through a decrease in half-value-layer is usually determined by exposure considerations. It is desirable to keep the exposures used in diagnostic roentgenology as small as possible. One important reason is that the risk of radiation injury to the patient is, to some degree, proportional to the magnitude of the exposure. The least exposure that can be used is dictated by factors associated with image quality. Some of these factors are associated with the final stage in the imaging process and the production of the visible image. These factors will be considered later. Other factors associated with the production of the x-ray image are considered here.

Since information is carried by variations in exposure rate across the beam, it follows that if the exposure rate of any part of the beam is reduced to zero, there can be no information carried by that part of the beam; therefore, the exposure rate must be at least great enough so that absorption by any tissue of interest does not reduce the beam to zero. Since absorption increases as the half-value-layer of the beam decreases, the use of a lower half-value-layer beam requires a greater exposure to the patient.

A practical lower limit of the exposure rate that can carry information results from the fundamental nature of x rays. The production of x rays is a random process, as is the absorption of x rays; therefore, every x-ray beam has associated with it statistical variations in exposure rate throughout the beam, and consequently across a plane transverse to the beam. In the x-ray image, these random variations are superimposed on the variations, which are coherently related to the tissues, through which the beam has passed. The relative magnitude of random variation increases as the exposure rate decreases; thus, at low exposure rates, the random variation can become a significant fraction of the average exposure rate, and consequently of the magnitude of the coherent variations across the x-ray beam. Under these conditions, a fraction of the x-ray image carries no information, and generally represents a "noise" that may mask the coherent variations (2).

THE VISIBLE IMAGE

The final stage in the imaging process is the transformation of the x-ray image into a visible image. This is carried out through the use of one of several possible "photoreceptors."

One such photoreceptor is the fluorescent screen. The rate of light emission from a fluorescent screen is linearly dependent on the rate of energy deposition in it, and hence is proportional to the exposure rate at the screen. When the fluorescent screen is positioned transversely to the x-ray beam emerging from the patient, a pattern of varying light intensities is displayed across the screen. This pattern corresponds to the pattern of exposure rates in the x-ray image.

In this fluoroscopic process, the visible image exists only as long as x rays are incident on the screen. An alternative process is used to make a permanent record of the image. In this procedure, termed roentgenography, the photoreceptors are radiographic films or combinations of radiographic films and fluorescent screens. Our present interest is with the measurement of the characteristics of the photoreceptors used in roentgenography. The fluoroscopic process will not be considered further. The terms "radiography" and "radiograph" will be used in future discussions as less cumbersome synonyms for "roentgenography" and "roentgenograph."

When radiographic film or film — screen combinations are used as photoreceptors, the visible effects are the result of the total exposure to the film rather than exposure rate. When the film is exposed, energy deposited in the film induces a change in silver halide crystals contained in the x-ray sensitive part of the film. Subsequent chemical processing reduces the altered crystals to metallic silver. The quantity of metallic silver in any particular area of the film is directly related to the x-ray exposure received by that area of the film. The radiographic image is obtained when the processed film is viewed by light transmitted through the film. The pattern of light intensities, determined by the distribution of opaque metallic silver, is the inverse of the pattern of x-ray exposures. Areas that have received large exposures contain greater quantities of silver and hence transmit less light.

RADIOLOGICAL OPTICS

The study of the properties of a radiological image that determine image quality, the quantitative definitions, and their interrelationship with image quality is called radiological optics. Since this report is concerned with the characteristics of photoreceptors, and primarily as they relate to image quality, a brief discussion of radiological optics and the definition of some terms used in this field are appropriate.

DENSITY

The radiographic image appears as a pattern of light intensities transmitted through the exposed and processed film. Light transmission through a radiograph is usually expressed in terms of the optical density of the radiograph. Optical density is defined as

$$D = \log_{10} \frac{1}{T} \qquad (1)$$

where D is the optical density and
T is the fractional light transmission through the radiograph.

Exposure and processing are usually adjusted to produce an average density across the radiograph of 1.0 (3).

The useful range of density of a medical radiograph extends from a minimum of 0.3 to a maximum of 1.7 (3). The term "density units" is often used to specify a density difference. In this terminology, the above density range would be said to be 1.4 density units.

CONTRAST

Contrast, as a general term, refers to the relative difference in light emission from two points in an image. In a radiographic image, the light emission is in effect the light transmission through the film, and hence can be related to the density of the film. Quantitatively, contrast is defined as

$$C = |D_1 - D_2| \tag{2}$$

where C is the contrast and D_1 and D_2 are the optical densities of the points in question on the radiograph. Contast is never expressed as a negative value, therefore the absolute value of $D_1 - D_2$ is used in this definition.

Contrast is one of the fundamental properties of a radiographic image which determine image quality. It is the property of the image by which variations of the condition of tissues in the body are visually perceived.

Contrast is determined by the exposure difference in the x-ray image and a second factor which is associated with the photoreceptor. Each photoreceptor has a characteristic response in terms of the density change obtained for a given exposure difference; thus, a given x-ray image may produce radiographic images with differing contrasts when various photoreceptors are used.

UNSHARPNESS AND RESOLUTION

If there is a sharp line of demarcation in the tissues of the body (a bone-soft tissue interface, for example), this will appear in the image as a line of some width. To describe this feature of the image, the term unsharpness is used. Unsharpness is defined quantitatively in terms of the width of a line in the image corresponding to a sharp edge in the object. The degree of unsharpness is determined by physical factors affected by all stages of imaging process.

Unsharpness affects the image of large objects by blurring the edges; however, if the objects of interest in the body happen to be small and positioned near each other, the unsharpness may cause these objects to appear in the image as a single object. In this case, the objects have not been resolved or resolution is inadequate. Resolution is defined quantitatively in terms of the numbers of "lines" per unit length that can just be resolved in the radiographic image. The factors affecting resolution are essentially those that affect unsharpness, and consequently are also associated with all stages of the imaging process. Additionally, resolution is inherently dependent on the contrast of the image. Objects are visually resolved in an image only if the density difference between the image in question and the immediate surrounding area is perceptible. Perception depends on contrast; therefore, a high-contrast image will, under certain conditions, provide better resolution.

MODULATION TRANSFER FUNCTION

When an attempt is made to correlate all the various factors associated with the imaging process and their effect on image quality, numerous difficulties are encountered mainly because of the classical geometric definitions of unsharpness and resolution. Many of these difficulties have been overcome in recent years through the application of the modulation transfer theory to the field of diagnostic roentgenology (4).

The application of the modulation transfer theory to roentgenology is probably best explained in a brief and qualitative manner through comparison with a more common but analogous application. A signal can be transferred through electronic systems in the form of a time-modulated voltage. In its transfer through a particular component of a system, the modulation may be altered by characteristics of that component. The mathematical relationship between the modulation of the signal fed into the component and that which emerges from the component is called the modulation transfer function of the component. The modulation may be a complicated function of time, but it can be reduced to the sum of a series of sinusoidal modulations through the use of Fourier analysis. The usual practice is to express the modulation transfer function of the component in terms of its effect on sinusoidal modulations of various frequencies. One aspect of the transfer function is the reduction in the amplitude of the sinusoidal modulation that occurs in the transfer. In this case the transfer function contains the ratio of output amplitude to input amplitude as the dependent variable and the frequency as the independent variable. The transfer function of a system comprising a number of components in series is the product of the functions of each individual component.

The radiographic imaging system can be considered as one in which x-ray signals are transferred through various components of the system. The nature of the signal is different from that in electronics, but the fundamental concepts are applicable. The x-ray signal consists of variations of exposure rate across the beam. These are analogous to the variations of voltage in the electronic signal. While the electronic signal varies with time, the exposure rate varies with spatial position. The variation of exposure rate may be a complicated function of position, but Fourier analysis is equally applicable to this set of variables; consequently, the variation of exposure rate with position can be considered as the sum of a series of exposure rates varying sinusoidally with position. As such they may be expressed as spatial frequencies whose dimensions are cycles per unit length. The effect of a component of the imaging system on the x-ray signal can then be expressed as its transfer function in which the independent variable is spatial frequency and the modulation is exposure rate. The modulation can be equally well expressed in terms of exposure (the time integral of the exposure rate), since the independent variable is spatial rather than temporal frequency. As with the electronic system, the modulation transfer function of the entire imaging system is the product of the functions of each component in the system.

The transfer function of x-ray imaging systems is further comparable to that of an amplifier whose response falls below perceptible limits at high frequencies. Small objects in the body impress high spatial frequencies on the x-ray beam, therefore, if the modulation transfer function is low at these frequencies, the modulation created by this object may be so small at the output of the system that it is not detectable, and hence will not be visible in the radiographic image.

THE X-RAY IMAGE AND THE VISIBLE IMAGE

It is appropriate to review the interrelationships between the x-ray image and the visible image in the light of the subject matter presented up to this point. Each property of the visible image has its counterpart in the x-ray image. Exposure is transformed into optical density; contrast is the relative variation in density induced by exposure rate variations across the x-ray image. Unsharpness in the x-ray image will appear as unsharpness in the visible image. The unsharpness of the visible image is inevitably greater than that in the x-ray image. Objects are resolved in the x-ray image only if the difference between the exposure rate at points corresponding to the immediate surrounding area are detectable. These will be detectable in the radiograph if the contrast induced by the exposure-rate variation is visually perceptible; that is, if the modulation transfer function of the photoreceptor is adequate to display this modulation visually.

In summary, the quality of the radiographic image which results from a given x-ray image is governed by characteristics of the photoreceptor used in the imaging process. An objective decision as to which available photoreceptor should be used in a particular radiographic procedure can be made only if data on these photoreceptors are available.

PROSPECTUS

For various reasons, the effort expended on the investigation of the physical factors associated with diagnostic roentgenology has always been small in comparison with that spent on similar problems in the other fields of radiology. A consequence of this is that there does not exist today a comprehensive body of physical data on the various phases of this subdiscipline. Several years ago, a program of work on the physics of diagnostic roentgenology was established at The Johns Hopkins University. The general purpose of this program was threefold: (1) to carry out a fundamental study of the parameters of an imaging system that affect image quality; (2) to devise methods to measure these parameters; and (3) to make available to the field of radiology the results of these measurements on apparatus currently available in the United States.

One phase of this work concerned the radiographic film and combinations of radiographic film and fluorescent screens used in radiology. The number of available radiographic films and fluorescent screens can be combined to make over 200 different photoreceptors. Each photoreceptor has nine characteristics that affect image quality: speed, contrast factor, latitude, base density, fog density, reciprocity law failure, latent image fading, modulation transfer function, and "noise." Many of these characteristics are dependent on factors associated with the exposing radiation beam and the chemical processing of the film. To provide a comprehensive body of data on these devices, measurements of the characteristics of all photoreceptors were carried out over a wide range of exposure and chemical processing conditions.

Two of the characteristics — modulation transfer function and "noise" — have been the subject of separate research projects, and reports have been published on this work (2,5). The measurement of these characteristics will not be considered here.

To carry out the measurement of the seven remaining characteristics of the large number of available photoreceptors, and the effect on these characteristics of the variables mentioned above, it was necessary to develop a specialized laboratory system. Because the number of measurements to be made was very large, the system had to be adaptable to production-like procedures. At the same time, because the number of variables was large, the system had to be capable of considerable precision. Finally, since the data resulting from these measurements should be amenable to incorporation into a general body of data on diagnostic radiology, the measurements not only had to be accurate but expressed in appropriate and well-defined units. In the development of a laboratory system that would fulfill the first two requirements, commercially manufactured components were used when these were available; however, it was necessary to design and construct several key components that would enable measurements to be made with the required precision. The units in which the data are expressed were for the most part well established, but some of these were modified to make them more appropriate to the field of medical radiology.

A discussion of the characteristics of films and screens as they pertain to radiology and the definitions of the units of measurement in which these characteristics are expressed are contained herein. The experimental procedures used to measure the characteristics and the laboratory system used to carry out the experiments are described. In the description of the laboratory system, details are given on those components developed exclusively for the system. Finally, the manner in which the measurements were analyzed and a summary of the characteristics of radiographic films and screens currently available in the United States are included. Detailed data from the measurements are not included because of their bulk. These data, comprising about 100 pages of tables and graphs, will be published as a separate issue of the Environmental Health Series; however, a set of tables and curves are presented as an appendix to indicate the format in which the data will be published.

CHAPTER II.
RADIOGRAPHIC PHOTORECEPTORS AND THEIR CHARACTERISTICS

The photoreceptors used in radiography consist of either radiographic film or a combination of radiographic film and fluorescent screens. When film - screen combinations are used, the film is the component on which the image is recorded; the screen serves as an image amplifier or image intensifier. Fluorescent screens used in this manner are called intensifying screens.

RADIOGRAPHIC FILM

Radiographic film consists of silver bromide crystals uniformly distributed throughout a gelatin matrix, which in turn is coated on a thin sheet of transparent material. The crystal – gelatin suspension is called the film emulsion; the material on which it is coated, the film base.

In the film manufacturing process, impurities are incorporated into the silver bromide crystals to create imperfections in their crystal lattice. When energy is deposited in the crystals, a complicated mechanism involving both the crystal defects and subsequent chemical processing results in the deposition of metallic silver at the crystal site. A second stage in the chemical process removes the residual bromide from the emulsion. The gelatin matrix is transparent; hence light absorption by the processed film is predominantly due to the metallic silver.

The quantity of silver in any particular area of the film and hence the optical density of that area are determined by the properties of the emulsion, the energy deposited in the emulsion, and various factors associated with the first stage of the chemical process – the "development" of the film. The second stage of the chemical process (fixing) does not affect density unless the film is inadequately fixed, in which case residual silver bromide or other stains may absorb some light.

The emulsion absorbs only a very small fraction of the x-radiation incident on it, therefore the sensitivity of film to x rays, in terms of density per unit exposure, is almost linearly dependent on the emulsion thickness. There are practical upper limits to the emulsion thickness used; for example, the mechanical strength of the emulsion when it becomes wet during development. These problems are overcome to a certain extent by placing a layer of emulsion on both surfaces of the film base.

If radiographic film alone is used as the photoreceptor, energy is deposited in the crystals by the direct absorption of x rays. When film – screen combinations are used, energy deposition is by the absorption of light emitted by the screens. In general, the emulsion most sensitive to x rays is not the most sensitive to light; therefore, two general types of radiographic film are manufactured: that for use with intensifying screens or "screen-type" film, and that for use with x rays directly or "nonscreen" film.

FILM – SCREEN COMBINATIONS

The exposure required to produce adequate density in a radiographic film can be reduced by a factor of up to 50 through the use of a combination of radiographic film and intensifying screens. Intensifying screens consist of a layer of fluorescent material coated on a sheet of cardboard or cardboard-like material. Their response to x rays is that described in the introduction: the rate of light emission from an area of the screen is proportional to the exposure rate at that area. It follows that the quantity of light emitted from the area (the time integral of the rate of emission) is proportional to the exposure.

The film – screen combination consists of a sheet of radiographic film sandwiched between two fluorescent screens and with the light-emitting surfaces of the screens adjacent to the film. These devices are more sensitive than film alone because the fluorescent crystals absorb a greater fraction of the incident x radiation than does the film emulsion and they reemit a significant fraction of the absorbed energy as light photons. The light photons are, in turn, more readily absorbed by the emulsion than are x rays. The net result is a greater energy deposition in the film emulsion per unit exposure to the photoreceptor. Two fluorescent screens are used because one screen does not entirely absorb the incident x radiation. Since unexposed, unprocessed film is not totally transparent to light, the doubly coated film is still an advantage.

Because of their greater sensitivity, film — screen combinations are usually preferred over film alone for most radiographic procedures; however, the use of intensifying screens results in a loss of detail which for some procedures is unacceptable from a diagnostic point of view. In such procedures, radiographic film is used without intensifying screens. It is in these procedures that the more x-ray sensitive non-screen film is used.

THE H AND D CURVE

If the densities obtained in a photographic emulsion are plotted against the logarithm of the energies to which the emulsion has been exposed, the resulting curve has a considerable straight line portion which facilitates the specification of several properties of the emulsion. This curve is designated as an H and D curve, after Hurter and Driffield who first used it to characterize photographic emulsions (6).

A graph of density versus the logarithm of the exposure to a radiographic photoreceptor (in roentgens) does not exhibit any straight line portion, but it does provide a curve from which many characteristics of the device can be obtained. Although the exposure is expressed in a unit different from that in photography, this graph is also referred to as an H and D curve. The densities plotted in an H and D curve are those above base and fog density. Base and fog density are defined in a following section. Graph I in the appendix is a typical H and D curve for a film — screen combination.

LOG UNITS

The term "log units" is used in some of the discussion which follows to express the relative difference between two exposures. The number of log units (N) between two exposures (E_1 and E_2) is given by

$$N = \log_{10} \frac{E_1}{E_2} \qquad (3)$$

where E_1 is the larger of the two exposures.

PROPERTIES OF FILMS AND FILM – SCREEN COMBINATIONS

With the foregoing discussion and definitions it is now possible to describe in more detail the characteristics of imaging devices, the relationship of these characteristics to patient exposure or image quality, and to define quantitatively the terms used to describe these characteristics. Two major characteristics (modulation transfer function and noise) have been evaluated as separate projects and are not considered here.

SENSITIVITY AND SPEED

Figure 1 shows the density – exposure relationship of three photoreceptors: a nonscreen film (curve A) and two film – screen combinations (curves B and C). The insert in figure 1 shows a hypothetical variation of exposure in a transmitted beam.

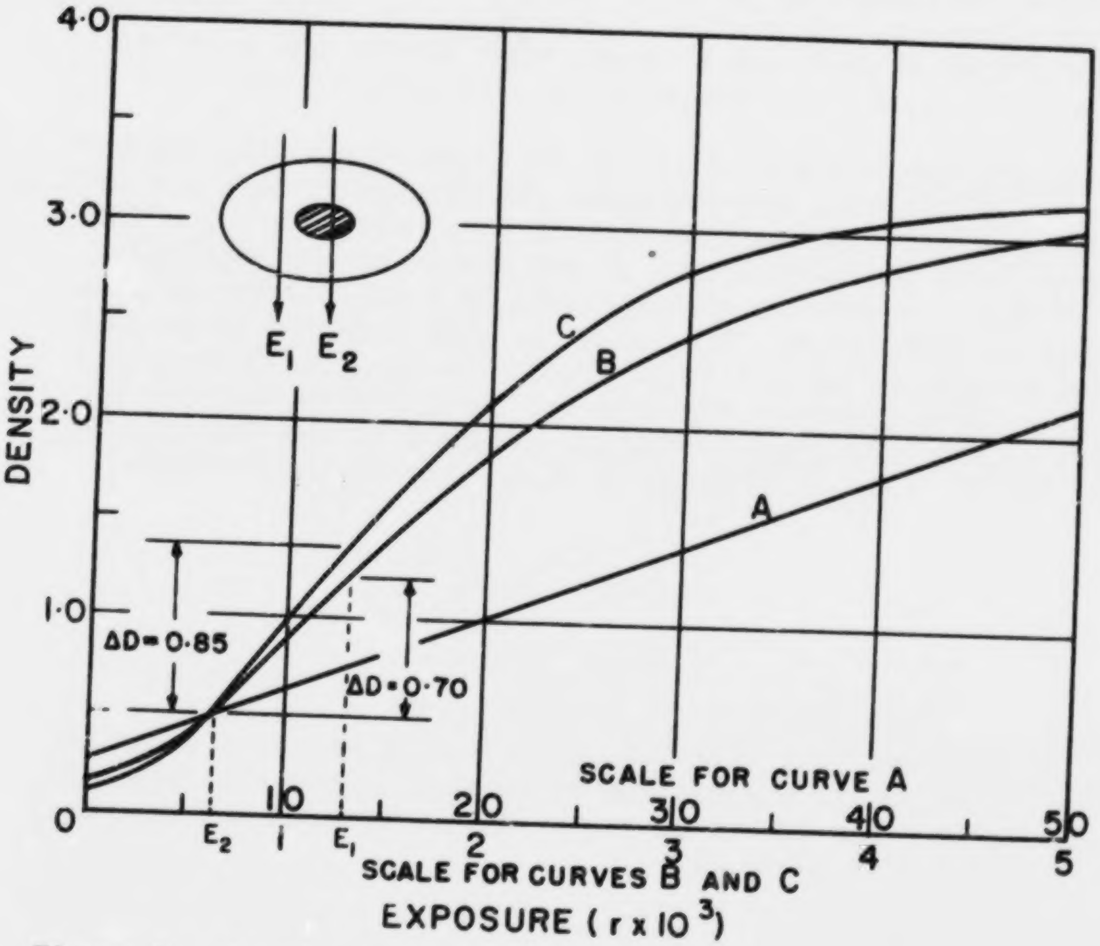


Figure 1. Density versus exposure relationship of three different photoreceptors. Curve A is that of a nonscreen film; curves B and C two different film – screen combinations. The insert shows hypothetical exposures E_1 and E_2 in a transmitter x-ray beam.

The significance of sensitivity is fairly obvious. If E_1 has a value of 1.25×10^{-3} R, an adequate density of about 1.2 will be produced by devices B and C, while a density of only 0.22 will be produced by A. The exposure to A must be increased by a factor of 20 to produce a density comparable to B and C. Since this will bring about an equivalent increase in patient exposure, sensitivity in terms of the exposure necessary to produce an acceptable density is an important characteristic of films or film – screen combinations.

The density – exposure relationships shown in figure 1 can be modified in various ways, one of which is to change development time. In general, a longer development time increases the film density produced by a given exposure. This increase as it relates to patient exposure is important, but it is not really an increase in the inherent sensitivity of the device. To remove the connotation that the basic sensitivity of the imaging device is being changed, the term "speed" is used to describe the exposure – density relationship for a given device under various conditions of exposure and development.

Speed (S) is defined as the reciprocal of the exposure in roentgens (R) required to produce a density of 1.0 above base and fog densities:

$$S = \frac{1}{R} \tag{4}$$

This definition of speed is identical to that given by the American Standards Association (7) to describe the sensitivity of a radiographic film, but standardized exposure and processing conditions are not inherent in the definition of speed as used here.

The inclusion of the phrase "above base and fog density" in the definition of speed is demonstrated in figure 1. When the exposure to the film or the film – screen combinations is zero, the density is not zero. There is a residual density because of two factors, film base and chemical fog, discussed in more detail below. Here it is only necessary to point out that the contribution which these two factors make to the total density is unrelated to the x-ray exposure; therefore, these are considered as separate characteristics of the film, and the definition of speed is written to exclude their effect.

By the above definition, the speeds of devices A, B, and C are 40, 810, and 925 R^{-1}, respectively.

CONTRAST FACTOR

The photoreceptor must be capable of transforming variations in exposure into variations in optical density — contrast. Referring again to figure 1, if E_2 is 0.625×10^{-3} R and the ratio E_1/E_2 is 2, device B will produce a contrast of 0.70 density units, while device C will produce a contrast of 0.85 density units; that is, B and C differ in the contrast they will produce for a given exposure ratio.

Several terms are used to specify the capability with which a photoreceptor transforms exposure variation into contrast. In photography, the term "gamma" is used. The gamma of a film is defined (6) as the slope of the straight line portion of the H and D curve,

$$\text{Gamma} = \frac{D_2 - D_1}{\log E_2 - \log E_1} \qquad (5)$$

where D_1 and D_2 are densities on the straight line portion of the curve produced by exposures E_1 and E_2, respectively. In radiography, since the H and D curve does not have a straight line portion, the gamma is defined (3) as the slope of a tangent to the curve at its steepest point. Its numerical evaluation is carried out through the use of equation (5), but now D_1 and D_2 are hypothetical values on the tangent corresponding to exposure E_1 and E_2. The American Standards Association defines an "average gradient" of a radiographic film (7) as "the slope of the straight line, drawn on the density — log exposure curve" obtained under standardized conditions "between the points on the curve at densities of 0.25 and 2.00 respectively, above the base and fog density; that is,

$$\text{Average Gradient} = \frac{1.75}{\log E_2 - \log E_1} \qquad (6)$$

where E_2 is the exposure corresponding to a density of 2.00 above base and fog, and
E_1 is the exposure corresponding to a density of 0.25 above base and fog."

For reasons mentioned below, it was considered preferable to use a new term and a new definition to specify the contrast — exposure relationships measured in this laboratory. The term "contrast factor" was chosen and defined as the slope of the H and D curve at density 1; that is,

$$\text{Contrast Factor} = \frac{D_2 - D_1}{\log E_2 - \log E_1} \qquad (7)$$

D_1, D_2, E_1, and E_2 are defined as in equation (5) except that D_1 and D_2 now lie on the tangent at D = 1.0 instead of on the tangent at the point of maximum slope. Equation (7) can be written more simply as

$$\text{Contrast Factor} = \frac{\Delta D}{N} \qquad (8)$$

where ΔD is the density change brought about on the tangent at D = 1.0 for N log units change in exposure.

Although the definition of contrast factor is akin to that of gamma as used in radiography, gamma was not used because the point of maximum slope on a radiographic H and D curve is very often near a density of 2.0; that is, beyond the upper limit of the range of useful density found in conventional medical radiographs. The choice of D = 1.0 was made because this density represents the approximate average density of medical radiographs.

When the determination of a number involves the tangent of an empirically derived curve, there is the possibility that some error will occur because of the difficulty of drawing a true tangent. On these grounds, it could be considered more advisable to use the American Standards Association term average gradient and its definition; however, the term is not appropriate because of the connotation of standardized procedures; the definition or a similar one was not chosen because the "latitude" of photoreceptors, described below, was to be defined in terms of two points on the H and D curve. Maintaining separate definitions for latitude and contrast provides an additional piece of information on the properties of the film or film – screen combination.

Figure 2 shows the gamma, average gradient, and contrast factor of a typical film – screen combination. For clarity, the same H and D curve is repeated at 0.2-log unit intervals.

LATITUDE

Latitude is a property of a photoreceptor, which is of secondary importance with regard to image quality of patient exposure. Radiologists may use the numerical value of latitude as an indication of the range of exposures over which a reasonable radiograph can be obtained. Since the normally useful range of densities found in radiographs is from 0.3 to 1.7, latitude is defined as the exposure change in log units required to bring about this density change; that is,

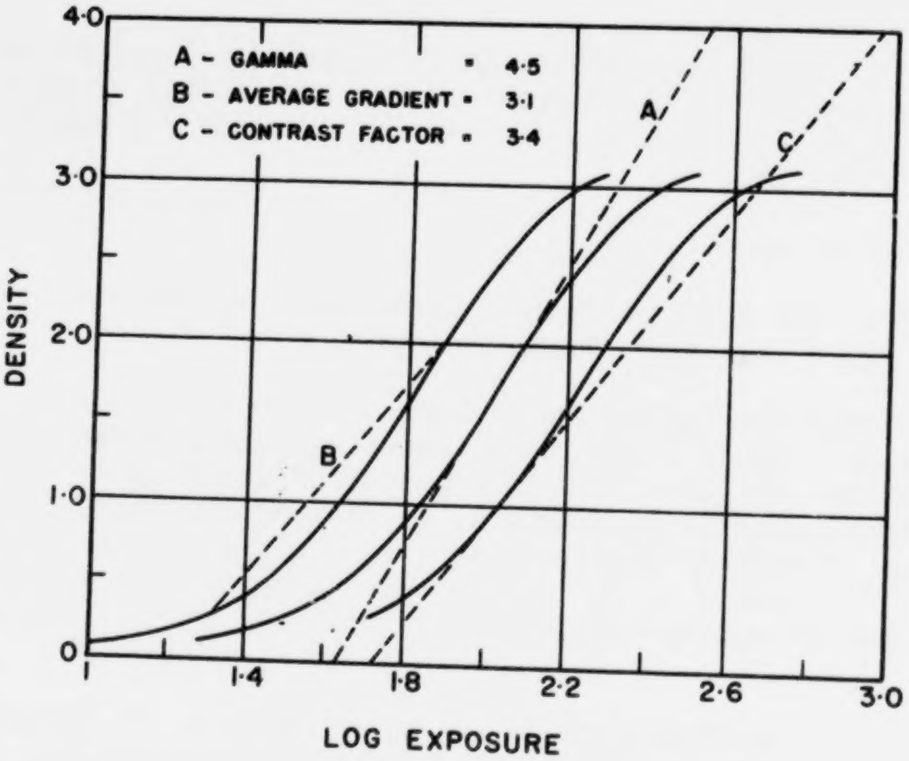


Figure 2. Gamma, average gradient, and contrast factor as determined from the H and D curve of a typical film — screen combination. For clarity, the curve is reproduced at 0.2-log unit intervals.

$$\text{Latitude} = N_r \qquad (9)$$

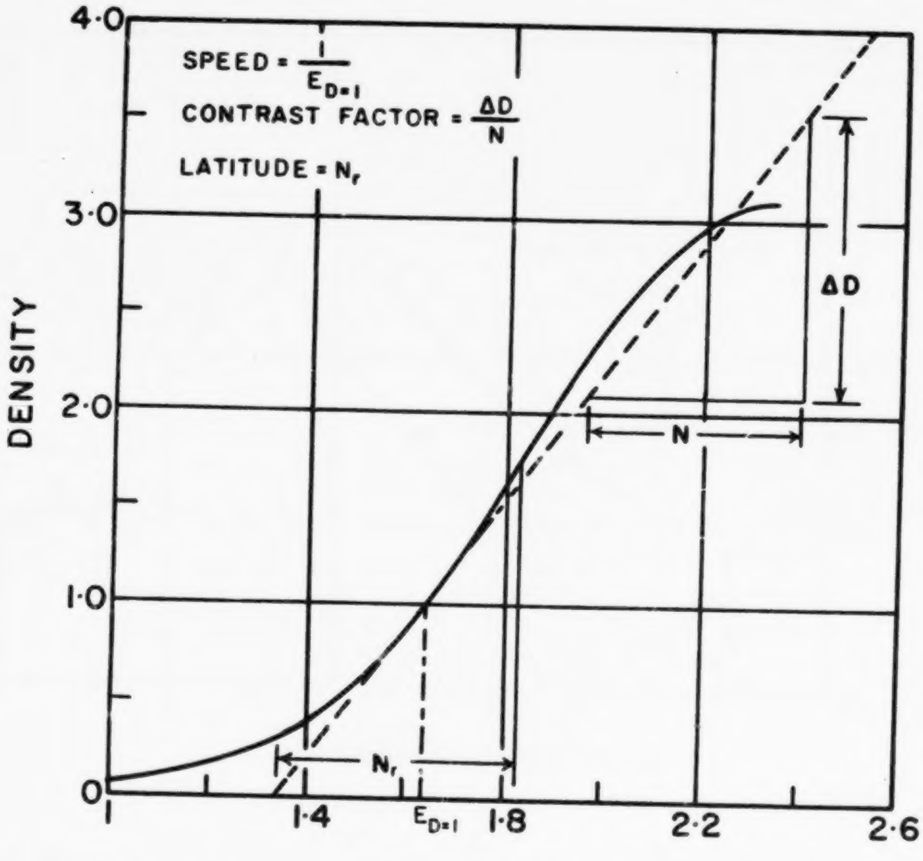
where N_r is the exposure change in log units required to change the density from 0.3 to 1.7.

The evaluation of latitude from an H and D curve is shown in figure 3.

FOG DENSITY

If a film is processed without receiving an exposure, it will exhibit a residual density (fig. 4). This density exists across the entire surface of the film and is the sum of two densities: (1) the film base on which the emulsion is coated is not entirely transparent and (2) the "chemical" fog in the emulsion.

Chemical fog is probably caused by several factors. Stray radiation from natural sources may deposit energy in many of the silver bromide crystals in the emulsion, permitting their reduction to metallic silver during chemical processing. A



LOG EXPOSURE

Figure 3. The evaluation of speed, contrast factor, and latitude from an H and D curve.

second source of energy that will create fog is thermal energy. A film stored at an elevated temperature will exhibit a fog density, which increases with storage time. When film is stored under low temperature conditions, fog increases with storage time but more slowly than at elevated temperatures; however, film recently received from the supplier still exhibits a fog density, which may be considered a true chemical fog. It is considered that silver bromide crystals not having received additional energy from any source will undergo reduction to metallic silver at a very slow rate during normal processing procedures. Evidence for this is found in the fact that chemical fog continues to increase with development time even when the density brought about by x-ray exposure has ceased to increase with development time.

The effect of fog density is to decrease the contrast of the radiograph exposed to a given density by exposure E_1. This effect can be understood if the fog is considered equivalent to an additional exposure across the entire film. An equal additive increase in E_1 and E_2 (fig. 1) would decrease the contrast by decreasing the ratio of E_1/E_2.

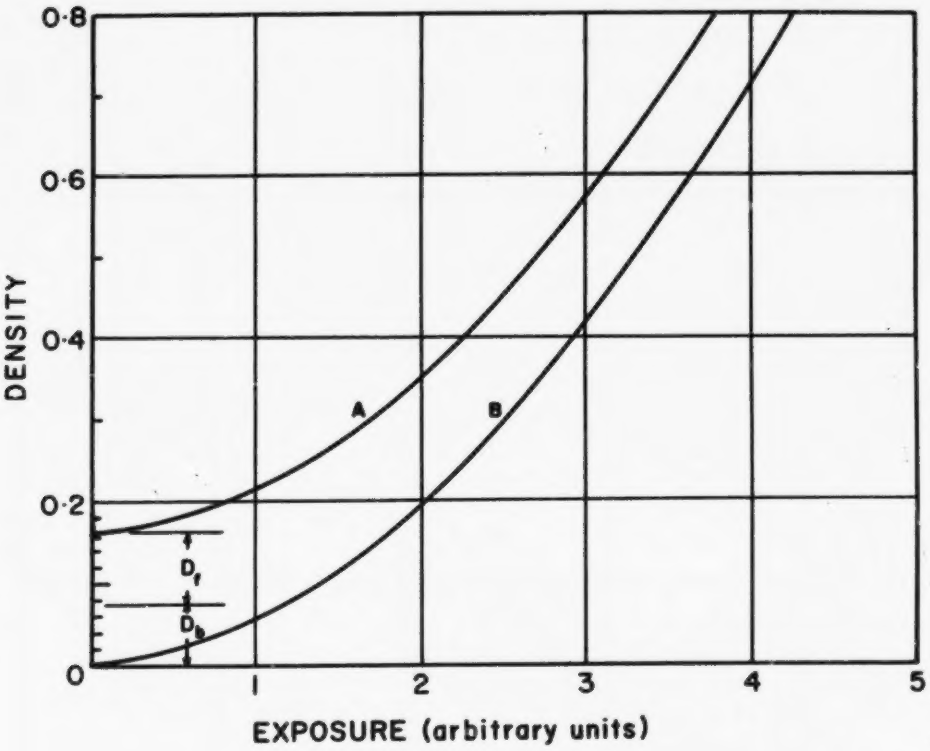


Figure 4. Density versus exposure curve (A) showing fog density d_f and base density d_b producing a density at zero exposure. Values are typical for a medium speed film. Curve B is the net density versus exposure curve; that is, with base and fog densities subtracted from the total density.

Fog density can be expressed as an optical density, and no further consideration of a unit to express this characteristic is necessary. The fog density may be different for different film types produced by one manufacturer or by different manufacturers. Because the fog density is a function of storage time and storage conditions, no attempt was made to assign a fixed value. Fog densities also vary with developer type, temperature, and development time. These variations are of interest to the radiologists and were determined in the course of the measurements.

BASE DENSITY

Part of the residual density of a radiographic film that has received no exposure is due to the base, on which the emulsion is coated, not being totally transparent to light. The film is said to have a certain base density — specified as an optical density. The effect of base density on the radiographic image is the same as that of fog density.

Base density is usually constant for film types produced by one manufacturer and in general will only change when the material of which the base is composed is intentionally altered.

RECIPROCITY LAW FAILURE

When a light sensitive emulsion is exposed to a given amount of energy in the form of light photons, the resulting density is primarily a function of the energy deposited in the emulsion and, to some extent, the time interval over which the energy is deposited. All other factors being constant, an energy E deposited at intensity I in 0.1 second will not necessarily produce the same density as an equal energy E delivered at an intensity 0.1 I over a time interval of 1 second. The failure of the emulsion to respond equally to energy delivered at different intensities is called "reciprocity law failure." Changes brought about by reciprocity law failure are referred to as reciprocity effects. There are no reciprocity effects when emulsions are exposed directly to x rays (8).

When film – screen combinations are used in radiography, only a small percentage of the total energy deposited in the film is due to the direct action of x rays. The balance is from light emitted by the intensifying screens. Radiographs made with film – screen combinations are therefore subject to reciprocity effects. The speed of a film – screen combination determined at an exposure time of 0.1 second may be different from that determined at other exposure times. Exposure times used in radiography may be as short as 0.008 second or as long as several seconds; therefore, it is desirable to determine the change in speed occurring over a similar range of exposure times.

LATENT IMAGE FADING

The exposure of a radiographic emulsion produces in the emulsion a pattern of "activated" silver bromide crystals, which when developed will yield the radiographic image. The pattern of activated crystals is called the latent image. The crystals tend to return to their lower energy deactivated state, and over a period of time the number of activated crystals decreases. This process is called "latent image fading." For this reason, the speed of a film or film – screen combination may also be a function of the time interval between exposure and development. This effect was also studied in the evaluation of the films.

FACTORS THAT MODIFY THE CHARACTERISTICS OF PHOTORECEPTORS

In the preceding section, several characteristics of photoreceptors were described: speed, contrast factor, latitude, fog density, base density, reciprocity law failure, and latent image fading. Three of these (base density, reciprocity law failure, and latent image fading) are characteristics of films only. They may be different for different films, but are inherent characteristics of the film and not subject to modification by factors associated with exposure, development, or the intensifying screen with which they are used.

Fog density is considered to be a characteristic of the film, but subject to modification by developer type, development temperature, development time, and the time and conditions of storage prior to exposure.

The remainder of the properties: speed, contrast factor, and latitude are considered to be characteristics of the entire photoreceptor and are different for each nonscreen film and each combination of screen-type film and intensifying screen. They are considered to be modified by developer type, developer temperature, development time, and the half-value-layer of the x-ray beam to which they are exposed.

The following chart summarizes the characteristics of photoreceptors and those factors presumed, at the beginning of the measurements, to affect each of the characteristics.

Speed Contrast factor Latitude	determined by	Film type Screen type Half-value-layer Developer type Developer temperature Development time
Fog density	determined by	Film type Developer type Developer temperature Development time Storage time
Base density Reciprocity law failure Latent image fading	determined by	Film type

There are other factors that will affect several of the characteristics; for example, oxidation or chemical exhaustion of the developer, degree of agitation during development, and exposure of the film to extraneous light or ionizing radiation. These were not considered as parameters against which to measure the characteristics but rather as experimental conditions that had to be controlled while measurements were being made. Experimental procedures were established to ensure that such factors were held constant during all measurements, and that they were maintained at levels that would yield optimum values of the characteristics being measured.

NUMERICAL EVALUATION OF THE CHARACTERISTICS

With the exception of base density and fog density all the characteristics of photoreceptors are conveniently obtained through the use of H and D curves produced under the prescribed conditions of exposure and development. Speed, contrast factor, and latitude may be determined directly from the curves as shown in figure 3. Reciprocity law failure and latent image fading are expressed as changes in speed, therefore these also are evaluated from a series of H and D curves.

The ordinate of an H and D curve is density above base and fog density; hence the production of the curve requires that the combined value of these two properties be measured. With the use of a previously determined value of base density, fog density alone can be evaluated by a simple subtractive procedure.

A method used to obtain base density is to "clear" an unexposed, undeveloped sample of film by fixing it about 10 minutes in freshly prepared chemicals. The density of this film, after it is thoroughly washed and dried, is considered to be the base density of that film type.

CHAPTER III. EXPERIMENTAL DESIGN

OBJECTIVES

The primary objective was to obtain data on all radiographic photoreceptors available to radiologists in the United States. These data were to consist of the numerical evaluations of the characteristics of the photoreceptors under various conditions of exposure and development. The publication of these data in a well-organized format would require that they be analyzed to determine the manner in which each characteristic varies with exposure and development conditions. It follows that in this analysis a secondary objective would be achieved; namely, the demonstration of the relative effect of each factor on the characteristics of the imaging devices and on patient exposure or image quality. Pursuing this reasoning to its logical limit, the data could further show that the characteristics are independent of some of the factors generally considered to modify them.

SCOPE OF THE EXPERIMENTS

Letters were sent to all known suppliers of radiographic film and intensifying screens requesting samples of those items they marketed. In response to these letters, samples of 5 different nonscreen films, 13 different screen-type films, and 17 different intensifying screens were received. Since each screen-type film can be used with each type of intensifying screen, this represented 221 different film – screen combinations. These together with the 5 nonscreen films made a total of 226 photoreceptors. The films and screens on which measurements were carried out are listed in table 1.

Letters were also sent to all known suppliers of x-ray developer chemicals. These resulted in the receipt of six developers commonly used in manual development procedures and five developers for use in automatic x-ray development apparatus. These are listed in table 2.

Table 1. Films and screens on which measurements were carried out

Films	Screens
Ansco Fine-X	Ansco Medium Speed
Ansco High Speed	Ansco High Speed
Ansco Nonscreen	Auer Flash Speed
DuPont Cronex I	Buck A
DuPont Cronex II	Buck AA
DuPont Cronex III	Buck AAA
Ferrania Radio N	Ilford Standard
Ferrania Simplex (nonscreen)	Ilford Fast
Gavaert Curix Special	Patterson Detail
Gavaert Curix	Patterson Par-Speed
Gavaert Curix Rapid	Patterson High-Speed
Gavaert Osray (nonscreen)	Radelin UD
Ilford Standrad	Radelin HR
Ilford Red Seal	Radelin T
Ilford Ilfex (nonscreen)	Radelin TF
Kodak Blue Brand	Wolf Rapid
Kodak Royal Blue	Wolf Ultra
Kodak No Screen	

Table 2. List of developers used in the measurements of the characteristics of radiographic film

Manual	Automatic
Ansco Liquid	Ansco Liquamat
DuPont Liquid	DuPont Automatic
Ferrania Manual	Ferrania Automatic
Gavaert Gavadel	Hunt Graph-o-mat
G.E. Supermix	Kodak X-o-mat
Kodak Liquid	

It was felt that those characteristics considered to be modified by x-ray beam quality should be evaluated at 3 half-value-layers; those characteristics considered to be modified by development temperatures should be evaluated at four different temperatures; and those characteristics considered to be modified by development time should be evaluated at about six different development times. The half-value-layers, development temperatures, and development times used in the measurements are specified below where the individual experiments are described.

The number of possible combinations of characteristics to be measured, photoreceptors, half-value-layers, developer types, developer temperatures, and development times is in excess of 500,000. If definite values were to be determined for each combination, then the results of the measurements would include this quantity of data. This is not necessary, however, because all factors affecting the characteristics are not interdependent; for example, speed is determined by film — screen combination, half-value-layer, and all factors associated with development. The relative variation of speed with development factors is independent of the screen and half-value-layer. A complete program of measurements taking into account only the independent variables reduces the required number of data to about 20,000.

This program of measurements is still impractically large, and a further reduction of the program was made so that measurements could be completed in a reasonable time. This reduction was not considered to bring about a proportional reduction in the value of work for several reasons. The benefit of an overwhelming mass of data is doubtful, and many of the combinations would produce useless data. Of more significance is the fact that a series of measurements of typical variations could be carried out from which the values of other combinations could be interpolated with reasonable confidence. This would also serve to simplify the presentation of the data.

The series of experiments listed below were chosen as those that would provide an adequate and practical body of data, could be carried out in a reasonable time, and at a reasonable cost. The experiments may be considered as having been carried out in two phases. Phase I may be described roughly as the measurement of the characteristics under constant development conditions and phase II as the measurement of the characteristics under constant exposure conditions.

PHASE I. CONSTANT DEVELOPMENT CONDITIONS

EXPERIMENT 1

In order to determine the speed, contrast factor, and latitude of the photoreceptors when exposed to different quality x-ray beams, these characteristics of all films and film — screen combinations were measured at three x-ray beam half-valu -layers: 2-, 4-, and 6-mm Al. For these measurements, a commonly used manual developer (Kodak Liquid) was chosen and all films were developed for 3 minutes at a developer temperature of 20° C. This development time is less than that recommended by the developer manufacturer for a temperature of 20° C., but time — temperature relationships were to be determined in later experiments and the shortened development time would reduce experimental time appreciably. For each determination, five samples of each film type were used.

EXPERIMENT 2

To determine base density, reciprocity law failure, and latent image fading of radiographic films, base density was measured for all films by the method described in the previous chapter. Latent image fading was determined for all films through the measurement of speeds after various time intervals between exposure and development. The time intervals chosen were: "zero," 1 hour, 1 day, and 1 week. For the determination of latent image fading, screen-type films were exposed with Patterson Par Speed intensifying screens. This is a commonly used, medium-speed screen. Reciprocity law failure was determined for all screen-type films. Speeds were measured at four exposure times: 0.01, 0.1, 1.0, and 10.0 seconds. Films were exposed with an appropriate screen: Radelin TF. This high-speed screen was chosen because in previous experiments it had demonstrated good consistency, and it was sensitive enough to produce a density of 1 in low-speed films at reasonable exposure rates when exposed for 0.01 second. Development conditions and the number of film samples used were identical with those of Experiment 1.

EXPERIMENT 3

To check that the laboratory system and measurement procedures were not subject to gross variations, speed measurements made in Experiment 1 were repeated using an abbreviated laboratory procedure. In the original experiments, the average of five samples of each film type were used in the measurement of each characteristic. In the repeated measurements considerable time was saved by using only one sample of each film.

PHASE II. CONSTANT EXPOSURE CONDITIONS

EXPERIMENT 4

To measure the variation of speed, contrast factor, latitude, and fog density with development time and development temperature, these characteristics were measured for films processed in Kodak Liquid developer for six different development times: 2, 3, 4, 6, 8, and 12 minutes. The procedure was repeated at four different developer temperatures: 15°, 20°, 25°, and 30° C. Measurements were made on all nonscreen films, and on all screen-type films exposed with Patterson Par Speed screens. All exposures were made with an x-ray beam quality of 4-mm Al half-value-layer. In this and the following experiments, the number of film samples used in each determination was reduced to three. Precision checks on the previous measurements indicated that this lesser number would be adequate.

EXPERIMENT 5

To measure the speed, contrast factor, latitude, and fog density obtained with commonly used developer types, these characteristics were measured for films processed in two commonly used manual developers, Kodak Liquid and G.E. Supermix, and two commonly used automatic developers, Kodak X-o-mat and Hunt Graph-o-mat. Developer temperature was maintained at a value near that at which the developers were normally used: 20° C. for the manual and 30° C. for the automatic developers. Measurements were made at six development times: 2, 3, 4, 6, 8, and 12 minutes for the manual developers; 0.5, 1, 2, 3, and 6 minutes for the automatic developers. All other conditions were identical to those of Experiment 4.

EXPERIMENT 6

To measure the speed, contrast factor, latitude, and fog density of films processed in "recommended" developers, these characteristics were measured for films marketed by a particular company when processed in developers marketed by the same company. The combinations used were: all Ansco films in Ansco manual and automatic developers; all Ferrania films in Ferrania manual and automatic developers; all DuPont films in DuPont manual and automatic developers; all Kodak films in Kodak manual and automatic developers. Development was carried out at temperatures normally used for manual and automatic developers: 20° C. and 30° C., respectively. Measurements were made at the six development times specified in Experiment 5. All other conditions were identical with those of Experiments 4 and 5.

The chronological order in which the experiments were carried out was not necessarily that in which they are listed above. The chronological order chosen was that yielding the most measurements in the shortest time; for example, it was more efficient to carry out all measurements involving a particular developer temperature as a single series. Each time the temperature control system was reset, there followed a period of varying temperature as the system approached temperature equilibrium. During this period of several hours' duration, films could not be processed with the required precision.

It may be noted that the series of experiments involved several sets of duplicate measurements; for example, Kodak Liquid developer was used in Experiment 4 as well as in Experiments 1, 2, and 3, and it was one of the recommended developers in Experiment 6. Also, some of the development times and developer temperatures were identical in these experiments. If duplicate measurements did not involve a disproportionate amount of time, they were carried out as a periodic check on the consistency of the results. If the time involved was long, data from the previous experiments were used where duplication was required.

GENERAL PROCEDURE

Since the numerical evaluation of the characteristics of photoreceptors is carried out through the production of an H and D curve, the general procedure was to produce this curve for each condition of exposure and development prescribed by the experiment. The production of the H and D curve may be considered to involve three distinct steps: exposure of the photoreceptor, development of the film, and densitometric measurement of the processed film. Figure 5 is a photograph of three samples of processed film from which an H and D curve was derived. This was obtained as listed below.

EXPOSURE

The sample of film was placed in an x-ray cassette with the desired intensifying screen. The cassette was placed behind a lead shield in which a slot had been cut to permit a narrow rectangular beam of x rays to reach a small area of

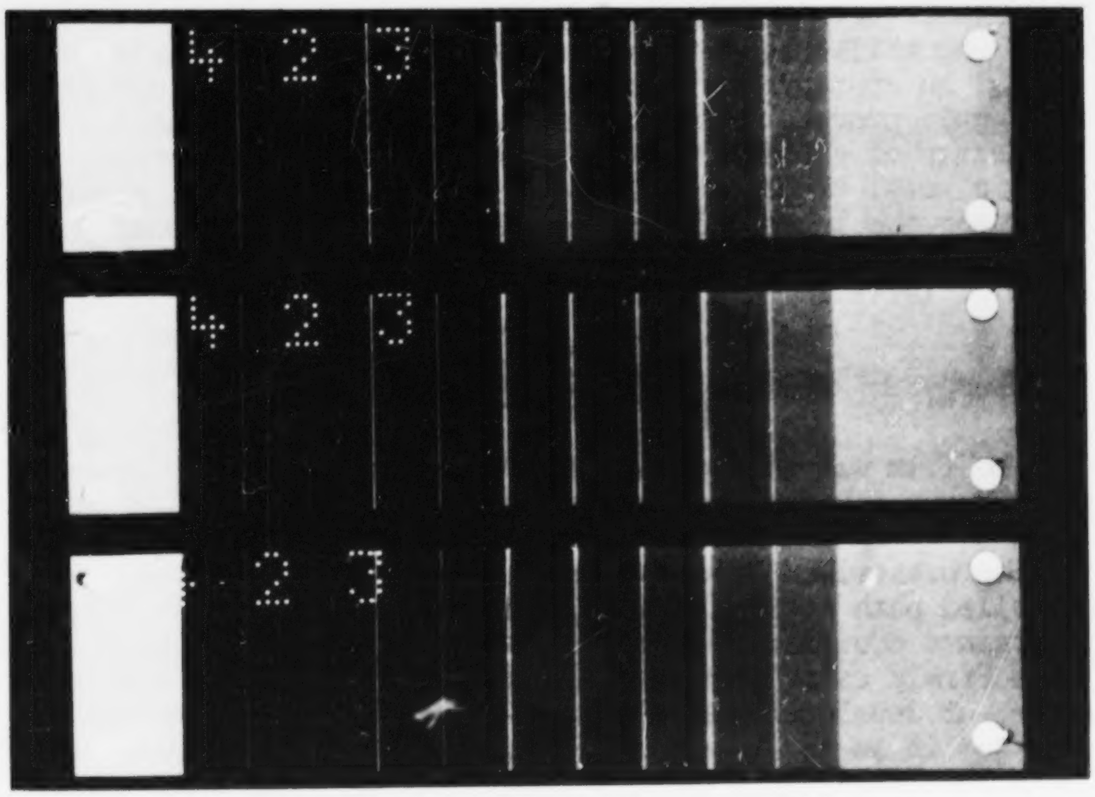


Figure 5. Approximately full-size photograph of three samples of exposed and processed film from which an H and D curve was derived.

the imaging device. This area was exposed to a known quantity of radiation. The cassette was then moved laterally until a different area of the film – screen combination was opposite the slot. A second known exposure, different from the first, was made on this area. This procedure was repeated until the device had received a series of gradated exposures that would produce in the developed film a range of densities extending from less than 0.3 to greater than 1.7. The procedure with nonscreen films was identical to this except the film was placed in a cassette not containing intensifying screens.

To avoid reciprocity effects, all exposures to film – screen combinations were made at a fixed exposure time of 0.1 second. This exposure time was chosen as an approximate median exposure time used in radiographic procedures. Since nonscreen films required greater exposures it was found more convenient to increase exposure time rather than exposure rate. This did not introduce an additional variable since film exposed directly to x rays does not exhibit reciprocity effects. To evaluate reciprocity effects in film – screen combinations, exposure time was of course varied.

Exposures to the photoreceptors were varied by changing the distance between the photoreceptor and focal spot of the x-ray tube while the exposure rate from the tube was held constant at an appropriate value. Each step in distance was that which would produce a change in exposure of 0.15-log unit. Each series of exposures was made with nine of these steps, giving a total range of 1.35-log units, or a factor of about 20 between the least and greatest exposure. The range of exposures produced a range of densities adequate for the evaluation of latitude in all photoreceptors.

DEVELOPMENT

The film was then processed under the development conditions prescribed by the experiment.

The prescribed developer was placed in the temperature-controlled bath at least 12 hours before it was used to allow temperature equilibrium between the developer and the bath to become firmly established. The number of films processed in one lot of developer was very small compared to that normally processed in an equal amount of developer in radiographic installations. This was done to avoid any possibility of chemical exhaustion of the developer. Frequent checks showed that exhaustion did not take place.

During development of the film, the developer was continuously agitated in a vigorous manner. The degree of agitation was well in excess of that necessary so that any loss of agitation time during the transfer of films in or out of the developer would not affect the measurements.

A stop bath was used to quench development action immediately upon removal of the film from the developer. Fixing time was kept safely above that usually considered adequate. Both fixer and stop bath solutions were changed frequently. Fixer, stop bath, and developer were kept at identical temperatures to prevent reticulation of the emulsion. Films were thoroughly washed in continuously changing water held at a temperature very near that of the processing solutions. Films were dried in a commercially built anhydrous drier operated at a temperature moderately above room temperature.

DENSITOMETRY

Film densities were measured with a MacBeth-Ansco Densitometer, Model 12A. This instrument meets the American Standards Association requirements for the measurement of diffuse transmission density (9). The densitometer was calibrated with a step wedge provided by the MacBeth-Ansco Company and compared with a step wedge obtained from the Kodak Company. No difference was found.

After the densitometer had been properly calibrated and set to zero, a sample of the film type under evaluation, cleared for the measurement of base density, was placed in the densitometer light beam. If this base density had not been previously measured, the density was noted. The densitometer was then set to zero with this film in the light beam. The cleared film was then replaced by the film under evaluation. A portion of this film, which had received no x-ray exposure, was introduced into the light beam. The density of this area was then measured and noted. This measurement was the fog density of the film. The densitometer was again set to zero with both base and fog in the light beam, and the densities of areas that had received various exposures were measured. Since the densitometer was set to zero with the base and fog in the light beam, measured densities were those above base and fog.

The calibration of the densitometer was checked before and after each day's measurements to ensure that the sensitivity of the instrument had not changed. The precision of the densitometer was stated by the manufacturer to be ± 0.02 density units. Successive measurements of the step wedges confirmed this statement.

CHAPTER IV. CONTROL OF X-RAY EXPOSURE RATE

The number of variables that affect the characteristics of photoreceptors is large; hence, it is necessary to provide for the adequate control of each of these variables if the characteristics are to be measured with a reasonable precision. In experiments involving the use of an x-ray generator, uncontrolled variation of exposure rate can be a major source of error and one of the more difficult to overcome. The source and nature of these variations were investigated and considerable time was devoted to the development of an exposure-rate stabilizer that would reduce these variations to a satisfactory level. In addition to the precise control of exposure rates, the stabilizer circuit provided a means by which the quantitative value of each exposure could be easily and rapidly determined.

The exposure system used in the experiments was designed to take full advantage of the stabilizer, and the design requirements of some other components of the exposure system were set by its mode of operation. For these reasons, a description of the entire exposure system is simplified by a prior discussion of the stabilizer. This chapter is therefore devoted to a discussion of the problem of exposure-rate control, and a description of the stabilizer. The entire exposure system is described in the following chapter.

PARAMETERS OF X-RAY PRODUCTION

In an x-ray tube, electrons released from a heated filament are accelerated toward a tungsten target by an electric field established between the filament and the target. The electrons reach the target with an energy determined by the field strength, which, in turn, is a linear function of the potential applied between the x-ray tube electrodes. There is a probability that interactions between electrons and charged components of the target atoms will result in the conversion of a fraction of the electrons' energy into photons

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of x radiation. Both the probability of x-ray production and the average energy of the x-ray photons produced increases with the energy of the electron as it reaches the target. Since electron energy is determined by the potential across the tube (kilovoltage or kV), a change in kV will change both the average photon energy and the rate at which radiation is emitted from the target. Average photon energy determines beam quality, while the exposure rate is a function of the rate of photon emission from the target and the energy distribution of these photons; therefore, both beam quality and exposure rate vary with the kV across the x-ray tube.

For a given kV across the tube, the rate of x-ray production is also a direct function of the rate at which electrons strike the target; that is, the rate of charge transfer across the tube or x-ray tube current. X-ray tube current is usually measured in milliamperes (mA).

For a given x-ray tube, kV and mA are the only factors that determine the exposure rate at the tube's exit port. External to the tube, the exposure rate is modified by distance (inverse square law) and attenuation by whatever absorbing material may be interposed in the path of the x-ray beam. It follows then that the exposure rate at a point in space can be varied by changing the kV across the tube or the mA through the tube, and that it will remain constant only if these two factors are carefully controlled.

CONVENTIONAL CONTROL OF kV AND mA

The usual methods of control can be explained with the use of figure 6, which shows a simplified circuit diagram of a conventional x-ray generator. There are numerous subcircuits which are not shown in this diagram. In this figure, T-1 is a high-voltage transformer whose output is in the kilovoltage range required for x-ray production. D is a bridge-type rectifier which converts the a.c. output from the transformer to the fully rectified wave form that appears across the x-ray tube. A is an autotransformer that, in conjunction with contacts C-2 and C-3, provides a method by which the voltage applied to the primary of T-1 and hence the kilovoltage across the x-ray tube can be changed. M-2 is a meter that measures the a.c. voltage applied to the primary of T-1. This meter is usually calibrated to indicate the voltage that will appear across the x-ray tube when the exposure is made. This calibration takes into account the turns ratio of T-1, voltage losses in T-1, and voltage losses in the rectifier.

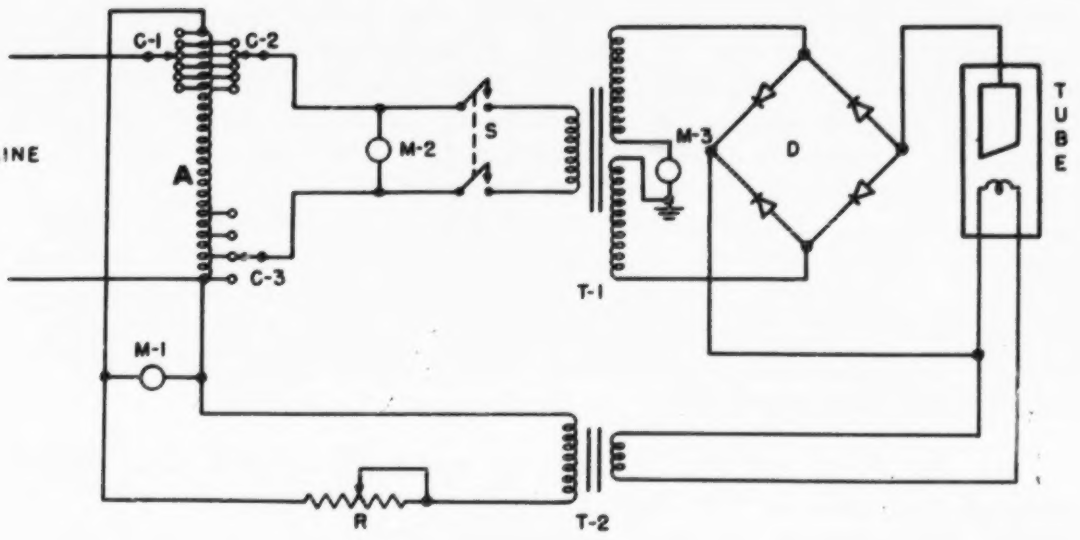


Figure 6. Simplified circuit diagram of an x-ray generator.

There is the possibility of considerable error in the calibration of this meter. This is not too important if the generator is thoroughly calibrated with regard to beam quality and exposure rate at various meter readings. More important is the fact that changes in the transformer, rectifier, or several subcircuits can occur causing a change in the potential across the tube but will not be reflected in the meter reading. These changes can occur between calibrations but are more likely to occur while the generator is in operation.

In many units, including the one used in this laboratory, meter M-2 is not included in the circuit, and the control knobs with which C-2 and C-3 are adjusted are calibrated to indicate the voltage that will appear across the tube. In this case, variations in voltage across the powerline to the generator would produce an undetected change in the voltage across the x-ray tube. To display these variations, voltmeter M-1 is placed across the autotransformer. The voltage across the autotransformer may be considered as the input voltage to the generator. To compensate for line voltage variations, a set of contacts C-1 are provided on the autotransformer. Prior to making an exposure, the line compensator C-1 is adjusted until M-1 indicates some predetermined value. C-1 can be moved only in finite steps, each of which produces a 1-percent change in the input voltage.

An x-ray tube is operated under temperature-limited conditions; that is, the flow of electrons across the tube is limited by the electron emission of the filament, hence by the temperature of the filament. The filament is heated with power taken from the autotransformer at a voltage preset by the line compensator. When a tube is operated at low mA, a rheostat, R, can be used to control the fraction of this voltage that appears across the primary of T-2. This, in turn, controls the power to the filament and hence its temperature; thus the x-ray tube current is controlled by rheostat R. T-2 serves primarily as an isolation transformer, but it is also used as a stepdown transformer to reduce the applied voltage to the range in which x-ray tube filaments are designed to operate.

X-ray tube current is usually measured with a d.c. milliammeter located in the high-voltage circuit near the point at which this portion of the circuit is grounded. It is shown as M-3 in figure 6. Since tube current is measured directly, it is subject only to errors associated with the milliammeter.

One further point concerning x-ray circuits will be of consideration when the timer – shutter mechanism is discussed. X-ray exposures are normally initiated and terminated by application and removal of the high voltage across the x-ray tube. This is performed with a relay located on the line side of T-1, the contacts of which are shown as S in figure 6.

UNCONTROLLABLE EXPOSURE RATE VARIATION

Measurements were made to determine the magnitude of variations in exposure rate that could be expected from a conventional diagnostic x-ray generator. To determine the effect of line voltage variation on exposure rate, the x-ray tube current was set to an initial value near that at which measurements on the photoreceptors would be made, the input voltage across the autotransformer was varied, and the exposure rates at the various input voltages were measured. The line compensator was used to vary the input voltage. The results of these measurements are shown in figure 7. This graph shows that a 1-percent change in line voltage would produce about a 40-percent change in exposure rate. Part of this variation was due to changes in kV across the x-ray tube and to changes in tube current brought about by the variation in power delivered to the x-ray tube filament. Since the line voltage can only be compensated to about ± 0.05 percent, the exposure rate could not be controlled to better than ± 20 percent, even if the line

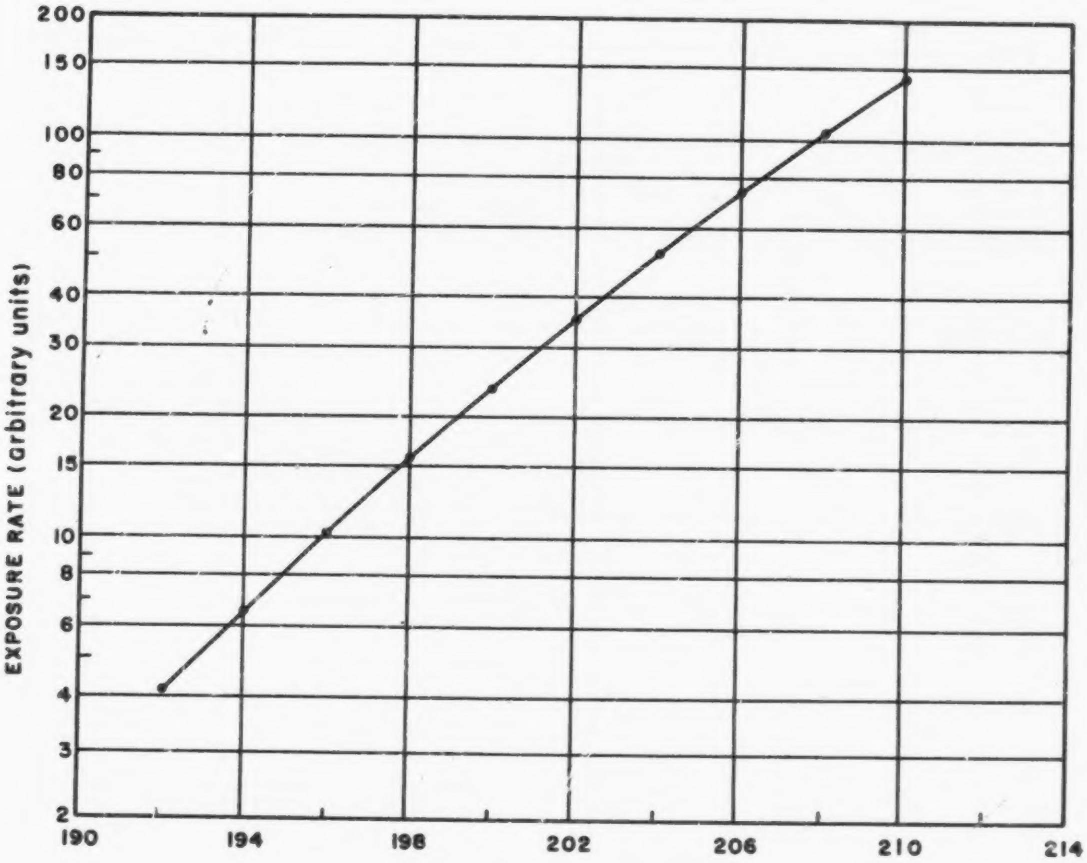


Figure 7. Variation of exposure rate from a conventional diagnostic x-ray generator as a function of the voltage applied to the x-ray generator.

voltage were carefully monitored during exposures. Monitoring both line voltage and tube current would reduce this variation; however, the milliammeter on a conventional x-ray generator cannot be read with a precision of better than ± 0.1 mA. The tube currents to be used in the experiments would average about 2 mA, and in several experiments would be a few tenths of a mA. This prohibited any effective monitoring of the tube current. While more precise milliammeters could have been added to the circuit, continuously monitoring these meters during the experiments would have been very time-consuming. A line voltage stabilizer was added to the system to reduce exposure-rate variations.

After the addition of the line voltage stabilizer, a second set of measurements was made. Exposures to the photoreceptors were to be 0.1 second in length and each series of exposures would be made over a period of a few minutes; therefore several series of measurements, each consisting of about 50 exposure-rate determinations for exposures 0.1 second in duration, were carried out. Each series of measurements was made over about a 3-minute interval. The results of two representative series of measurements are shown in figure 8.

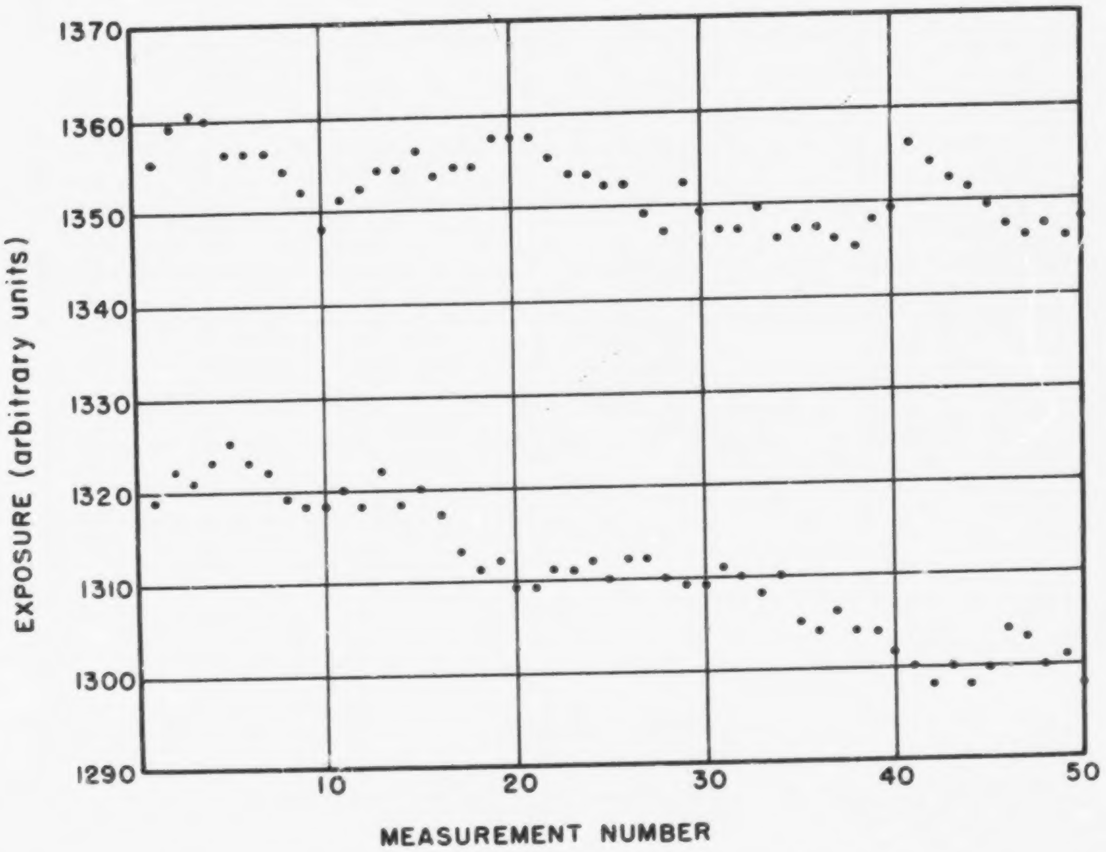


Figure 8. Uncontrolled variation of a series of 0.1-second exposures from a conventional diagnostic x-ray generator operated with a line voltage regulator.

In one series the exposure rate varied more or less randomly over a range of 1.5 percent. In the other series the exposure rate exhibited a drift downward over a range of about 2 percent. There is also considerable difference between the two sets of readings taken under presumably identical conditions.

These variations were considered to be in excess of that required for the experiments. It was felt that the principle of automatic feedback control might be useful in holding exposure rates constant. This would increase the precision of measurement and eliminate the need for continuously monitoring the x-ray controls.

The Automatic Control of Exposure Rate

If both beam quality and exposure rate must be held constant, then it is necessary to hold both kV and mA constant. If minor variations in beam quality are inconsequential, then exposure rate can be held constant by adjusting about by variations in kV. Insofar as the photoreceptor evaluation experiments were concerned, beam quality changes were considered relatively unimportant compared with exposure rate changes; therefore this principle was used in the design of the feedback system.

The system, shown schematically in figure 9-a, is a negative feedback amplifier. An ionization chamber C located in the x-ray beam produces an ion current proportional to the exposure rate from the x-ray tube. Positive ion current i_c, and negative current i_r from a reference source Z produce, at the input of an operational amplifier A, a potential proportional to the input but reversed in polarity. This voltage, applied to the control grid of beam power pentode T, controls the flow of current through the primary of a saturable reactor S, and thereby controls the a.c. impedance of the secondary of the reactor. The secondary, in series with the primary of the x-ray filament transformer, controls the x-ray tube current in a manner analogous to the rheostat control shown in figure 6.

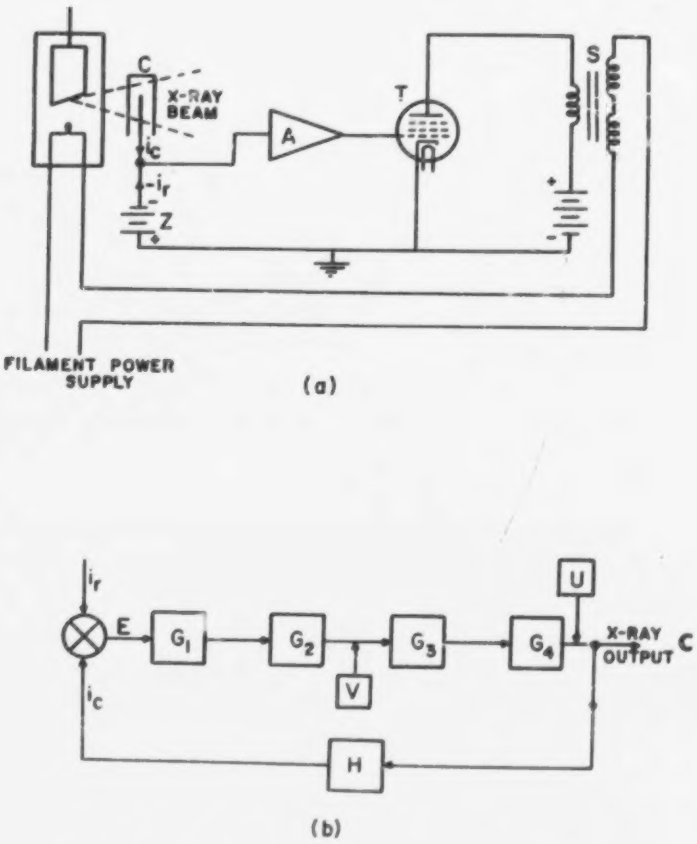


Figure 9. Schematic diagram (a) and block diagram (b) of the exposure-rate stabilizer.

If for any reason the exposure rate from the x-ray tube changes, the feedback loop will tend to return the exposure rate to its previous value. If, for example, an increase in kV were to occur, the exposure rate would increase and the ion current would increase. The net current, $i_c - i_r$, would increase and the input potential at A would become more positive. This would make the output potential of A more negative. The increased bias on the grid of T would decrease the current through the primary of S. This would increase the impedance of the secondary of the saturable reactor, decrease the power to the filament, reduce the x-ray tube current, and reduce the exposure rate from the tube.

To produce an intentional change in exposure rate, it is necessary only to change the magnitude of the reference current. The feedback system will then "call for" a different ion current to establish equilibrium conditions.

The optimum design of a feedback system can be obtained only through a complete analysis of the system and of the individual components in the system; however, some requirements can be seen from a very elementary analysis made with reference to figure 9-b, which is a block diagram of the system.

In figure 9-b, i_r and i_c are the currents from the reference source and ionization chamber, respectively. E is proportional to the algebraic sum of these currents. G_1, G_2, G_3, and G_4 represent the transfer functions of the operational amplifier, beam power pentode, saturable reactor, and the x-ray tube. The feedback component with a transfer function H is the ionization chamber. The constant of proportionality relating E to the algebraic sum of i_r and i_c is determined by the input capacity of the operational amplifier; therefore, it can be considered to be included in the transfer function G_1 of this component.

In general, transfer functions express all changes in a signal which occur between the input and the output of a component. In electronic systems, the changes may be in amplitude, phase, or wave form. Insofar as this analysis is concerned, only changes in amplitude are considered so that the transfer functions may be considered as d.c. amplification or gain.

From figure 9-b it can be seen that,

$$C = (G_1 \cdot G_2 \cdot G_3 \cdot G_4)\ E = G_t \cdot E \qquad (10)$$

where

$$G_t = G_1 \cdot G_2 \cdot G_3 \cdot G_4$$

and

$$E = (i_r - i_c) = (i_r - HC) \tag{11}$$

Combining equations 10 and 11,

$$C = i_r \frac{G_t}{1 + G_t H} \tag{12}$$

From equation 12 it can be seen that a change in i_r will bring about a linearly proportional change in C; that a change in G_t will not affect C if G_t is much greater than 1; and that a change in H will bring about a significant change in C unless G_t is much less than 1.

A disturbance in G_4, which affects C, may be considered as a signal introduced into the system by U (fig. 9-b). It can be shown (10) that the change C_u, which this will create in C, is given by

$$C_u = U \frac{1}{1 + G_t H} \tag{13}$$

Combining equations 12 and 13, the relative change in C is then:

$$\frac{C_u}{C} = \frac{U}{i_r} \cdot \frac{1}{G_t} \tag{14}$$

that is; the relative variation in C which would have been created by U is reduced by a factor $1/G_t$. The capability with which a feedback system controls variations in C is directly dependent on G_t; thus G_t should be made large. Referring again to equation 12, if G_t is large, then H must be held very constant.

Unwanted variations can occur in other components of the system. A disturbance in component G_2, for example, could be considered as a disturbance V injected in the system between G_2 and G_3. It can be shown (10) that the relative variation of the output C_v/C which this disturbance brings about is:

$$\frac{C_v}{C} = \frac{V}{i_r} \cdot \frac{1}{G_1 \cdot G_2} \tag{15}$$

that is; disturbances introduced into the system are reduced only by the transfer functions of the components between the point where the disturbances are introduced and the input of the system; therefore components near the input should be very stable and relatively free from noise. Components nearer the output end of the system need not be so rigidly controlled.

As indicated above, complete transfer functions express changes in amplitude, phase, and wave form and in addition must be expressed as a function of frequency. The gain of feedback system must be less than 1 at a frequency which produces a phase shift of 180°, otherwise the system will be unstable. This very often sets an upper limit to the gain that can be used with a particular system.

No attempt was made to carry out formal design procedures in the development of the feedback system being described here. It was found that a control system adequate for present purposes could be developed through semiquantitative design procedures, and trial and error adjustment of some critical components.

The circuit diagram of the exposure-rate stabilizer is given in figures 10 and 11. Figure 10 is the power supply only; figure 11 shows the other components of the unit. The various components are considered individually in the following section.

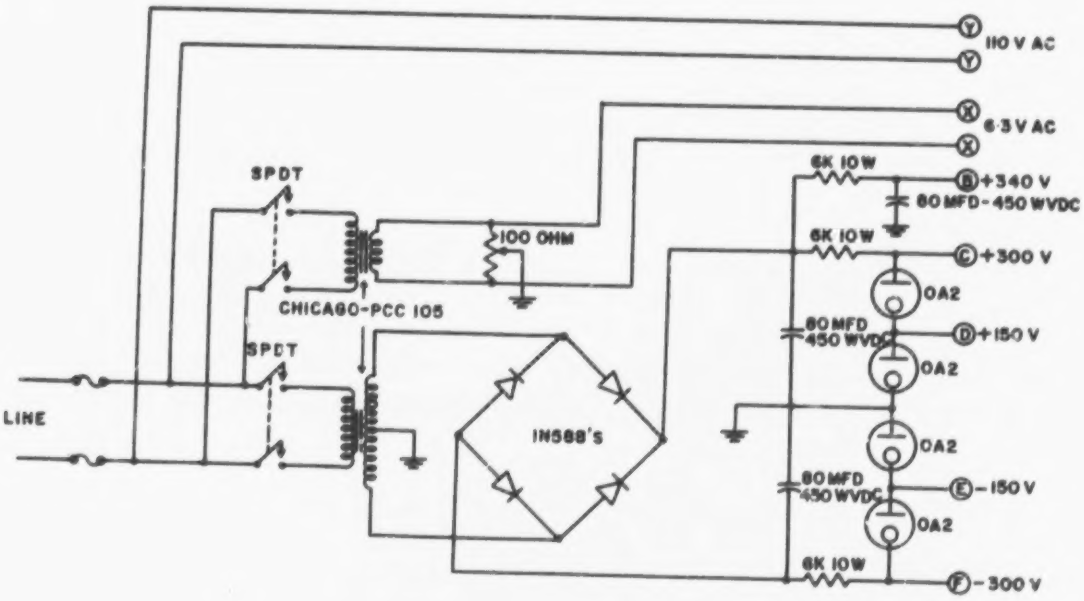

Ⓨ
110 V AC
Ⓨ
Ⓧ
6.3 V AC
Ⓧ
SPDT
100 OHM
CHICAGO-PCC 105
SPDT
LINE
IN588's
6K 10W
Ⓑ +340 V
80 MFD-450 WVDC
6K 10W
Ⓒ +300 V
OA2
80 MFD
450 WVDC
Ⓓ +150 V
OA2
OA2
80 MFD
450 WVDC
Ⓔ -150 V
OA2
6K 10W
Ⓕ -300 V

Figure 10. Circuit diagram of the power supply used with the exposure-rate stabilizer.

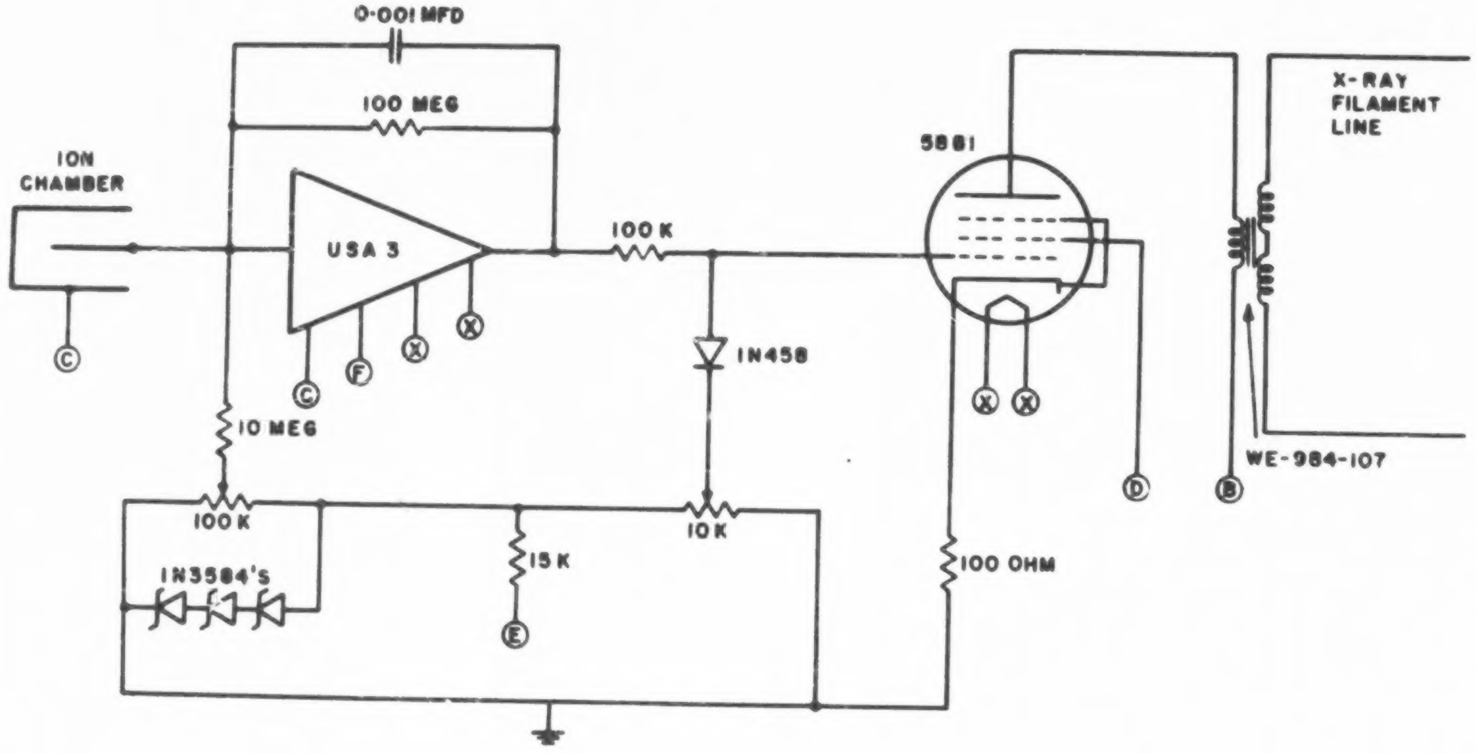

0·001 MFD
100 MEG
ION CHAMBER
USA 3
C
C
F
X
X
10 MEG
100 K
IN3584's
15 K
E
100 K
IN458
10 K
5881
X
X
100 OHM
D
B
X-RAY FILAMENT LINE
WE-984-107

Figure 11. Circuit diagram of the exposure-rate stabilizer.

FEEDBACK SYSTEM COMPONENTS

POWER SUPPLY

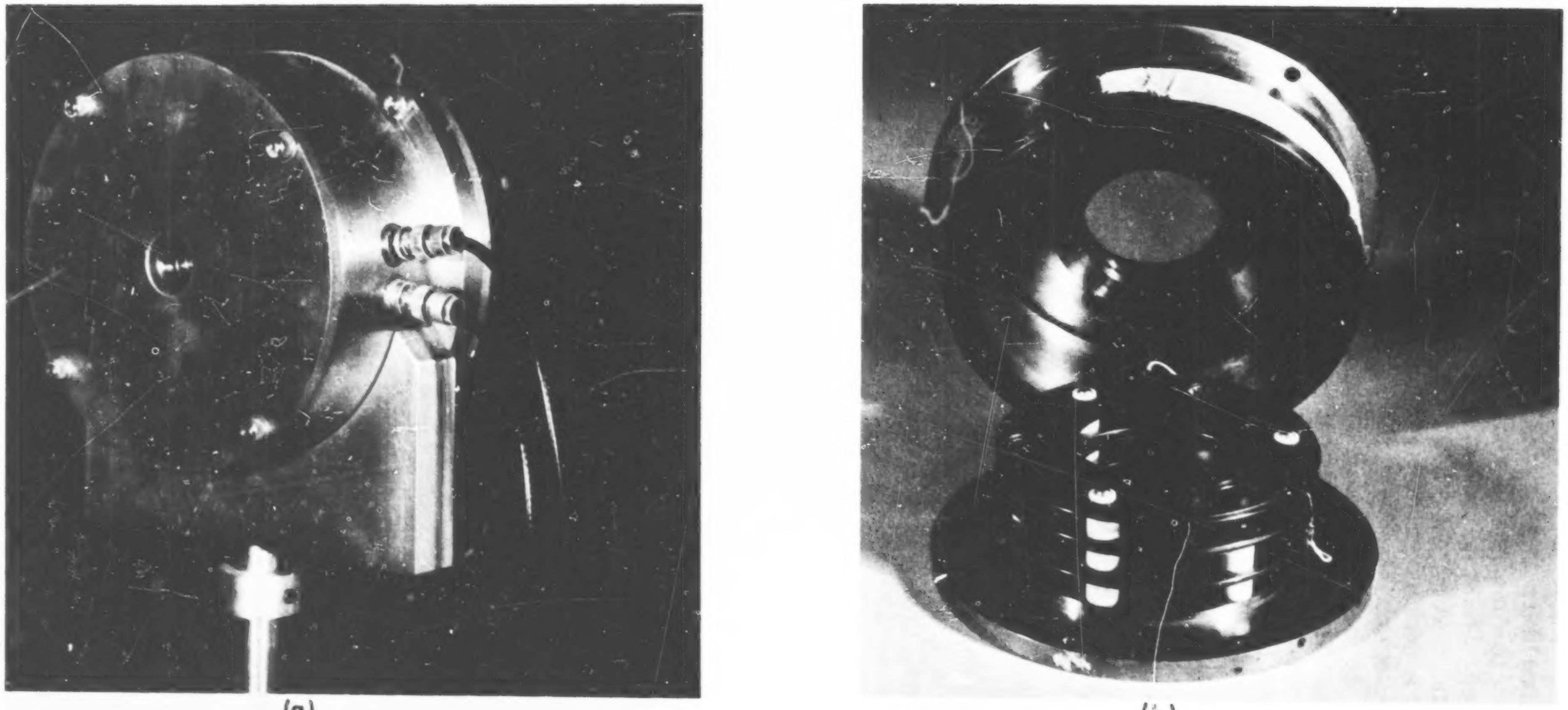
The power supply for various components of the feedback system is shown in figure 10. It provided +300 V and -300 V as the B supply to the operational amplifier, +300 V as the B supply to the 5881 beam power pentode, +300 V to the ionization chamber, +150 V to the screen grid of the 5881, and -150 V to the reference current supply. All d.c. supplies were regulated with 0A2 gas regulator tubes. A filament transformer supplied 6.4-V a.c. power to all tube filaments and to the operational amplifier vibrator.

The heating element of a temperature control oven, referred to below, was supplied by 110-V a.c. power shown as Y — Y in figure 10. This power was provided from the line side of the switches which controlled power to the other components. To avoid long delays while temperature equilibrium became established, the oven was disconnected only when absolutely necessary and for as short a period as possible. During normal use, the oven was in operation 24 hours each day.

IONIZATION CHAMBER

The primary requirements of the ionization chamber were that it provide an adequate signal in the form of an ionization current which varied linearly with the exposure rate from the x-ray generator, and that the ion current be independent of all factors other than exposure rate from the tube. In addition, a useful beam of radiation should be transmitted through the chamber without undergoing an unacceptable degree of filtration.

A photograph of the ion chamber is shown in figure 12. Figure 12-a is the assembled chamber; figure 12-b shows the electrode assembly. The electrode assembly consisted of three parallel plates in each of which a hole had been cut to transmit the useful beam through the chamber without additional filtration. Part of the cross-section area of the x-ray beam which entered the ionization chamber was incident on these plates, and the intensity of radiation beyond each plate could conceivably be reduced by absorption in the plate. If this absorption were significant, the ionization current would also be a function of the beam quality because the fractional transmission through the plates would vary with photon energy.



(a)

(b)

Figure 12. Stabilizer ionization chamber; (a) assembled chamber; (b) electrode assembly.

Plates of three different types of material were tried in the chamber: lucite on which a thin film of evaporated metal had been deposited; sheet aluminum plate approximately 0.5 mm in thickness; and a very thin aluminum foil. With none of these could there be demonstrated a significant dependence of ion current on beam quality over the narrow range of uncontrolled kV variation to be expected during a series of x-ray exposures. The aluminum foil, when stressed by the potential applied between the electrodes, tended to flex and produce transients in the ion current from the chamber.

Insulators used in the chamber were made of Teflon and the electrode support was arranged so that the central electrode from which the ion current was collected was supported only on the grounded case of the chamber. Since the input of the operational amplifier and hence the central electrode remain very close to ground potential, leakage current was to all practical purposes nonexistent.

For a given exposure rate, ion current is determined by the air volume from which ions can be collected. Maximum cross-sectional area was obtained by allowing almost the entire x-ray beam to enter the chamber. The final dimension of volume was determined by plate separation. Through the use of three plates, with the two outside plates held at a high potential with respect to the center plate, an effective chamber length of about 3 cm was obtained. The use of three plates rather than two to obtain this volume reduced the problem of ion recombination. If two plates had been used, a much higher collection potential would have been required to prevent significant recombination. A collection potential of 300 V was applied to the chamber.

The electrode assembly was housed in a heavy brass case to avoid ionization from stray radiation. That surface of the chamber mounted against the x-ray tube casing was shielded with an additional one-fourth of an inch thickness of lead. This heavy shielding was required because a significant amount of leakage radiation penetrates the x-ray tube casing at areas other than the port provided for the transmission of the useful beam. Leakage radiation is highly penetrating because it is heavily filtered by the tube casing, and again because of the heavy filtration, the quantity of leakage radiation is strongly dependent on the kV across the tube.

The chamber was hermetically sealed to remove the dependence of ion current on the temperature of the air in the chamber and on barometric pressure. Electrical connections to the interior of the chamber were provided by insulated inserts sealed into the brass wall. Holes were cut in the flat ends of the chamber to transmit the useful beam. These were sealed with 1/32-inch thick lucite windows. Two thicknesses of this material constituted the only additional filtration contributed by the chamber to the total filtration of the useful x-ray beam. During operation, the chamber was subjected to temperature changes which would normally produce over 10-percent variations in ion current. No change in x-ray output could be detected from this source; therefore, the seals on the chamber were apparently adequate.

REFERENCE CURRENT

The subcircuit which provided the reference current is shown in figure 11. A potential of -150 V from the instrument power supply was applied across three 1N3584 zener diodes in series with a 15,000-ohm resistor. A 10-turn potentiometer across the diodes was used to alter the voltage applied to a 10-megohm resistor and hence to adjust the reference current to the operational amplifier to that necessary to induce the required output.

The diodes chosen for the reference source were those which had a very low temperature coefficient. To further reduce temperature effects they were enclosed in a Bulova 500M oven which controlled temperatures to ± 0.05° C. The 10-megohm resistor was also enclosed in this oven to reduce current variation because of its temperature dependence.

During operation of the stabilizer, random variation of the potential across the diodes or across any part of the potentiometer could not be detected with a digital voltmeter whose precision was better than 1 part in 10,000. The variation in current flow through the 10-megohm resistor could not be measured directly, but the combined variation because of the reference voltage and the operational amplifier is equally important and is easily measured. The stability of this combination is discussed in the following section.

OPERATIONAL AMPLIFIER

The operational amplifier used in the feedback circuit was Model USA-3 manufactured by George A. Philbrick Researches, Inc. This amplifier has an internal open loop gain of 10^7; the forward gain could be varied by changing the value of the feedback resistor across the amplifier. This was the primary means used to vary the loop gain of the stabilizer system.

When a 500-megohm resistor was placed across the amplifier, the forward gain was high, and exposure rates, averaged over a 1.5-minute interval, varied by only a few hundredths of a percent during several hours of operation; however, with the gain at this level the system was highly unstable, and any abnormal disturbance would cause it to oscillate. For routine use in the laboratory the feedback resistor was reduced to 100 megohms. This reduced the gain to a level at which oscillation did not occur but which still provided good control of the exposure rate. Because the gain of the operational amplifier was a direct function of the value of the feedback resistor, this resistor was enclosed in the temperature control oven with the reference current components.

The stability of the amplifier was very good on a short-term basis. When the input voltage was supplied by the reference source described above, the standard deviation of the output voltage, measured as an average voltage over a 0.1-second interval, was 0.03 percent. The drift of the amplifier, after a 1-hour warmup period was 0.5 percent per hour. After longer warmup periods, drift was reduced even further. Since the effect of this drift on the exposure rate was reduced by the gain of the operational amplifier, its effect on the exposure rate from the tube was very small.

The voltage swing at the output of the operational amplifier as the x-ray beam is turned on is directly proportional to the exposure rate from the x-ray tube. The only errors that would be introduced were those due to a change of sensitivity of the ionization chamber and a change in the gain of the amplifier. These were found to be negligible and a digital voltmeter, used to measure the amplifier output with a precision of 0.1 percent, served as a monitor of the x-ray exposure rate while exposures were made to the imaging devices.

CLAMPING DIODE

When the x-ray beam was not on, the output of the operational amplifier was determined by the reference current only and consequently was positive. With the grid of the 5881 positive, large-plate currents would flow through this tube. To prevent damage to the tube, a 1N458 diode was connected from the grid to a negative potential as shown in figure 11. If the potential of the grid became more positive than the arm of the 10K potentiometer, the diode would conduct and the grid potential was then determined by the potentiometer. This also served as a safety device to prevent damage to the x-ray tube in the event of loss of control by the feedback system.

BEAM POWER PENTODE

This device served as a power amplifier which would provide adequate current to the saturable reactor and still operate well below its maximum rating. As a pentode, its plate current was relatively independent of the plate supply voltage. The 100-ohm cathode resistor provided about a 0.1 feedback fraction which reduced variations because of changes in the saturable reactor.

SATURABLE REACTOR

The saturable reactor used in the system was a Westinghouse WE-984-097. While the system was in the development process, the secondary of the reactor was placed in the x-ray filament circuit in series with a rheostat. The introduction of resistance at this point in the circuit decreased the gain of the system and the rheostat could be used to suppress oscillation. This avoided frequent shutdowns of the apparatus and the associated instabilities of a warmup period. In the final circuit, the saturable reactor supplied the only impedance in the filament circuit.

MEASUREMENT SYSTEM FOR STABILIZER EVALUATION

The usual secondary standard maintained in most radiological installations for the measurement of x-ray exposure is the Victoreen R-meter. This instrument is stable, free from sudden changes in sensitivity, and relatively free from maintenance problems; however, it is capable of a precision little better than 1 percent at midscale, is rather inconvenient to use for large numbers of measurements, and at the half-value-layers used in diagnostic radiology its sensitivity is dependent on the quality of the x-ray beam. For these reasons a free-air chamber was built, similar to that maintained at the National Bureau of Standards as the national standard for the measurement of the roentgen. It was not developed as a primary standard, but as an instrument that would provide a high degree of precision, would be considerably more sensitive than the Victoreen R-meter, and, as a free-air chamber, would not be subject to variations in sensitivity because of changes in beam quality. This device was used in all measurements made in the development and evaluation of the exposure-rate stabilizer.

In general, it was required to observe changes in exposure rate while the feedback system was in operation, as each component of the system was altered, or as the numerous parameters of the system were varied. Exposure rate was determined by integrating the charge collected from the free-air chamber over a known time interval. The system used in these studies is shown in figure 13.

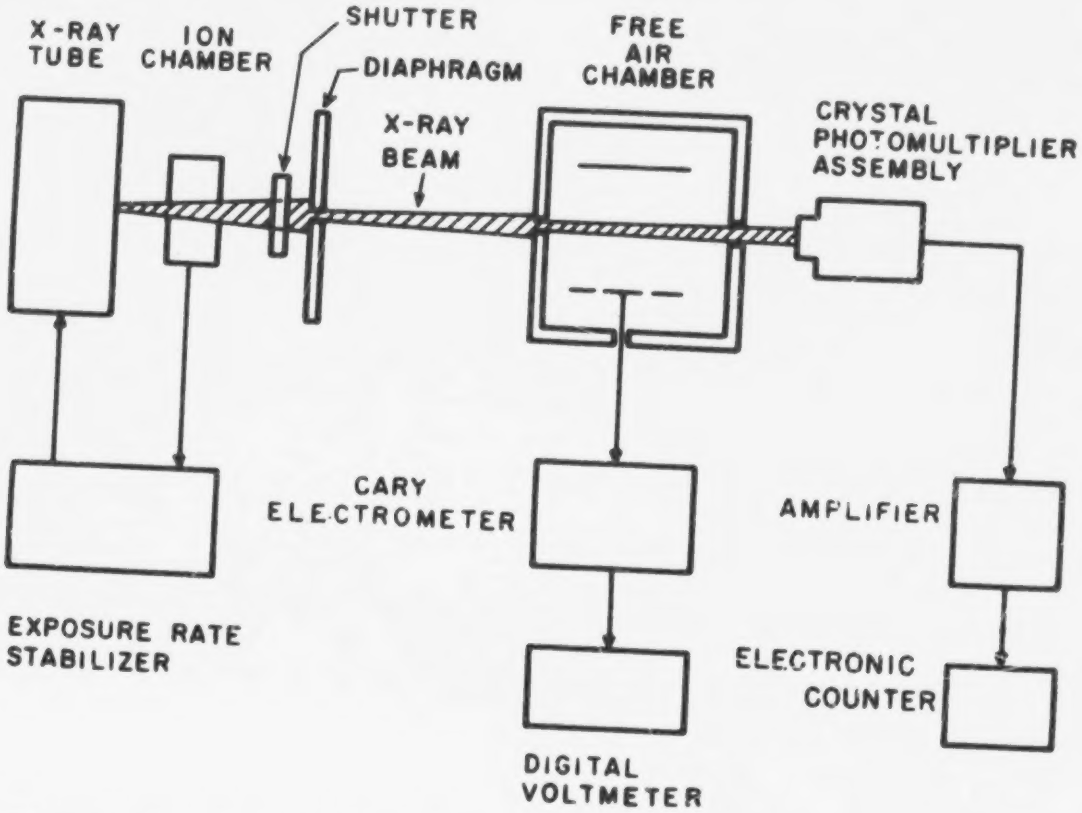

X-RAY TUBE
ION CHAMBER
SHUTTER
DIAPHRAGM
X-RAY BEAM
FREE AIR CHAMBER
CRYSTAL PHOTOMULTIPLIER ASSEMBLY
CARY ELECTROMETER
AMPLIFIER
EXPOSURE RATE STABILIZER
ELECTRONIC COUNTER
DIGITAL VOLTMETER

Figure 13. Schematic diagram of system used to evaluate the exposure-rate stabilizer.

The exposure was initiated by removing a shutter from the x-ray beam and terminated by reinserting the shutter. The exposure interval was timed with an assembly consisting of a scintillation crystal and photomultiplier tube combination, a d.c. amplifier, and a Hewlett-Packard 523B electronic counter. The electronic counter contained a precisely controlled 100-Kc oscillator which was used as an interval timer. The scintillation crystal was located so that it would be struck by x rays passing through the air chamber. When the x-ray beam was transmitted through the chamber, the signal from the photomultiplier tube triggered the timing mechanism on the counter. When the shutter was replaced in the x-ray beam, the decrease in signal from the photomultiplier tube terminated the time measurement. The electronic counter measured time intervals to 0.001 second in the mode in which it was used in these experiments. The actual exposure time was not determined with this accuracy because the amplifier used in the system had a finite time constant, and a finite time was required to remove and replace the shutter. Exposure times were of the order of 100 seconds, and the procedures were repetitive, so that the exposure times were probably measured with a precision of about 1 part in 10,000.

The charge collected from the air chamber was measured by a Cary electrometer. The instrument is supplied with a conventional "moving coil" voltmeter that could not be read with the required precision; therefore, a digital voltmeter with a precision of better than 1 part in 10,000 was used to measure the output of the electrometer. The electrometer is claimed to be consistent to 0.25 percent, but as far as could be determined, when used over the same region on one sensitivity range, its precision was better than 1 part in 1,000.

The ion collection potential for the air chamber was 1,500 V supplied by a highly stabilized power supply. At this potential, errors because of recombination were insignificant; however, the electrical capacity of the air chamber relative to the input capacity of the electrometer was sufficiently large that a change in collection potential would result in a significant redistribution of charge between these capacities. Measurements were made to ensure that variations in collection potential were not great enough to influence the quantity of charge detected by the electrometer.

Details of the procedures used in the analysis of the feedback system are beyond the scope of this report. With the measurement system described above, it was established that the voltage swing of the operational amplifier was a measure of the exposure rate over the range of uncontrolled kV changes to be expected during a series of measurements, and that exposure rates were controlled to about 0.1 percent during these exposures. Figure 14 is a scatter diagram of 50 exposure-rate measurements, each of which was averaged over a 0.1-second time interval with the exposure rate controlled by the feedback system. These measurements were made with a line voltage stabilizer in the x-ray circuit; therefore the relative variation of these exposure rates may be compared directly with the data in figure 8.

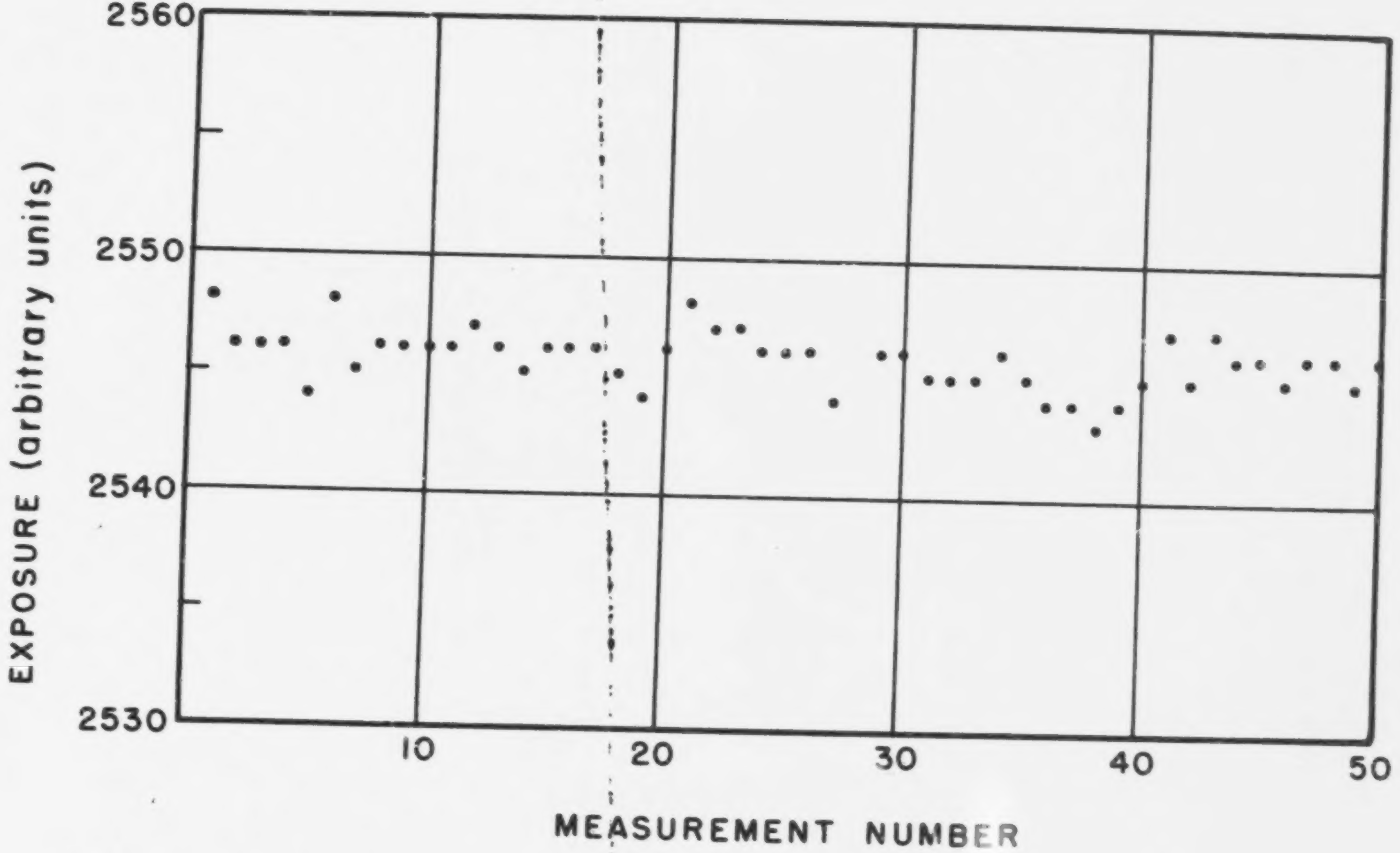


Figure 14. Variation of a series of 0.1-second exposures from a conventional diagnostic x-ray generator operated with a line voltage regulator and the exposure-rate stabilizer.

CHAPTER V. THE EXPOSURE SYSTEM

The exposure-rate stabilizer provided the precise control of exposure rate and a means to rapidly determine the exposure rate of any setting of the stabilizer. The balance of the system was designed as a means to produce each series of exposures simply and rapidly and to control exposure times precisely. A schematic diagram of the exposure system is shown in figure 15.

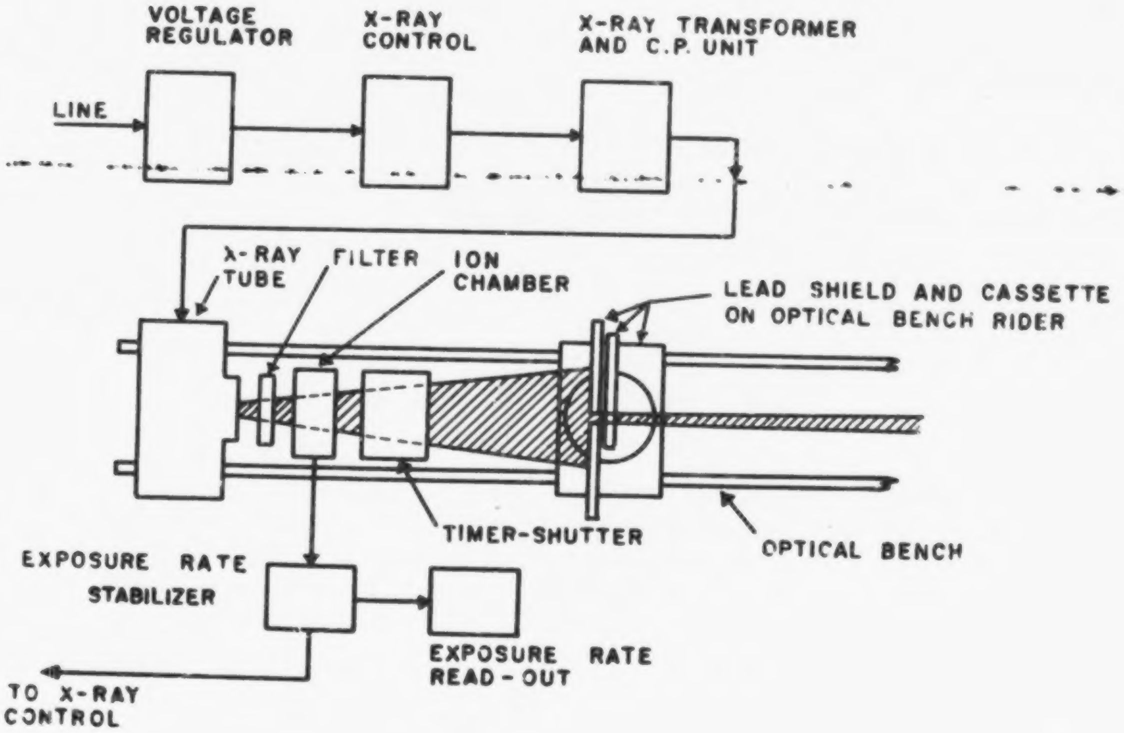

VOLTAGE REGULATOR
X-RAY CONTROL
X-RAY TRANSFORMER AND C.P. UNIT
LINE
X-RAY TUBE
FILTER
ION CHAMBER
LEAD SHIELD AND CASSETTE ON OPTICAL BENCH RIDER
TIMER-SHUTTER
OPTICAL BENCH
EXPOSURE RATE STABILIZER
EXPOSURE RATE READ-OUT
TO X-RAY CONTROL

Figure 15. Schematic diagram of the exposure system.

GENERAL DESIGN

The power to the x-ray generator was supplied through a line voltage regulator. The x-ray generator was a conventional diagnostic unit modified to adapt it to the laboratory system. One modification was the addition of capacitors and resistors to the high-voltage portion of the x-ray circuit to convert the high-voltage wave form across the x-ray tube from full-wave rectified to constant potential. The "C.P. unit" in figure 15 refers to this modification. Aluminum and copper filters were introduced into the x-ray beam to adjust beam quality to the required half-value-layer.

The x-ray beam, after filtration, passed through the ionization chamber of the exposure-rate stabilizer. The stabilizer and exposure-rate readout are shown in the diagram.

The x-ray tube was aligned so that the x-ray beam would travel parallel to the ways of a heavy-duty optical bench. A time – shutter mechanism which controlled exposure time was positioned on the optical bench just beyond the ionization chamber. An optical bench rider, on which a cassette could be mounted, provided the means to change distance and hence to vary exposures to the imaging devices.

The balance of this chapter is devoted to the description of the individual components of the exposure system, and the need that each component fulfilled.

LINE VOLTAGE STABILIZER

An initial reason for the incorporation of the line voltage regulator into the exposure system was given in the previous chapter. The exposure-rate stabilizer would have probably removed the need for the regulator, but since the regulator reduced input errors it also contributed to the precise control of exposure rates. As measurements progressed, it was found that at a beam quality of 2-mm Al half-value-layer, the speeds of film – screen combinations were quite dependent on beam quality. The line voltage regulator by reducing variations in kV also reduced errors from this source. The regulator used was a Sola Constant Voltage Transformer which attenuated voltage fluctuations by a factor of 10.

X-RAY GENERATOR

The generator used was a Westinghouse Autoflex control and transformer with a Machlett Dynamax 40 x-ray tube. The x-ray control circuit was modified to incorporate the exposure-rate stabilizer into the exposure system. For reasons associated with the control of exposure times, a further modification was made to convert the high-voltage wave form across the x-ray tube from full-wave rectified to constant potential.

FILTERS

Absorption curves in aluminum were determined with various kilovoltages across the x-ray tube. From these were selected the combinations of tube potential and added filtration that would produce x-ray beams with 2-, 4-, and 6-mm Al half-value-layers. A 2-mm Al half-value-layer was obtained with a tube potential of 75 kV and an added filtration of 0.64-mm Al; a 4-mm Al half-value-layer with a tube potential of 90 kV and 3.2-mm Al added filter; and a 6-mm Al half-value-layer with a potential of 90 kV and 7.7-mm Al added filtration. This last filter was too bulky for the space provided for the filters, and therefore some of the aluminum was replaced by copper. The filter used in the measurements was 0.15-mm Cu + 4-mm Al.

TIMER –SHUTTER MECHANISM

As indicated previously, when conventional x-ray generators were discussed, x-ray exposures are normally initiated and terminated through the application and removal of the high voltage across the x-ray tube. The exposure-rate stabilizer established precise control only after the x-ray beam had been on for several seconds; therefore exposure times were controlled through the use of a timer – shutter mechanism which interrupted the beam after it had passed through the ionization chamber of the exposure-rate stabilizer.

A photograph of the mechanism is shown in figure 16-a. A brass wheel, from which a sector has been removed, rotating across the x-ray beam transmits pulses of radiation through an aperature in the lead plate. The duration of these pulses is governed by the speed of rotation and the angle of sector that had been removed. A lead stop intercepts these pulses until it is intentionally removed from the beam. The sequence of events that results in a single pulse of x radiation transmitted along the optical bench is as follows. The x-ray beam is turned on and brought under the control of the exposure-rate stabilizer; the wheel is set in motion and allowed to reach equilibrium speed. When an "exposure" switch is closed, power is transmitted to the mechanism and the lead stop or shutter is removed from the x-ray beam through a timing sequence controlled by the rotating wheel. When the open sector of the wheel has just passed through the x-ray beam, a projection on the wheel closes a microswitch. If the exposure switch is closed, the microswitch activates a relay system that transmits and maintains power to a solenoid. The motion of the solenoid removes the lead shutter from the beam. Power maintained at the solenoid holds the shutter out of the beam until the open sector has again passed through the beam, transmitting an x-ray pulse along the optical bench. At this point in its rotation, the projection on the wheel again closes the microswitch, which now removes the power from the solenoid. A spring returns the lead stop to its original position to absorb any further x-ray pulses that may be transmitted by the wheel. A sequence of relays prevents the process from being repeated until the exposure switch has been released and again closed. The wiring diagram of the timer – shutter mechanism is shown in figure 16-b.

The four exposure times (0.01, 0.1, 1.0, and 10.0 seconds) used to measure reciprocity effects were obtained through combinations of two motors with speeds of 1.5 rpm and 150 rpm and two wheels with sectors of 90° and 9° removed. The exposure times were checked by observing on an oscilloscope the duration of the x-ray pulse transmitted by the motor – wheel combination during each revolution. While these times were being measured, the x-ray unit was operated under full-wave rectified conditions. Under these conditions the individual x-ray pulses produced by the pulsating potential could be used as a time base on which to measure the duration of the x-ray pulse.

If the potential across an x-ray tube is not constant, the instantaneous value of the exposure rate will vary with the voltage across the tube. If the voltage pulse is not perfectly symmetrical, or the exposure time does not embrace an integral number of pulses, the total exposure will be governed in part by the position on the voltage pulse at which the exposure is initiated. In conventional radiographic timers, the initiation and termination of an exposure is phased with the line voltage to avoid exposure variations from this source. This was not possible with the timer – shutter mechanism; therefore, the voltage across the x-ray tube was converted to constant potential.

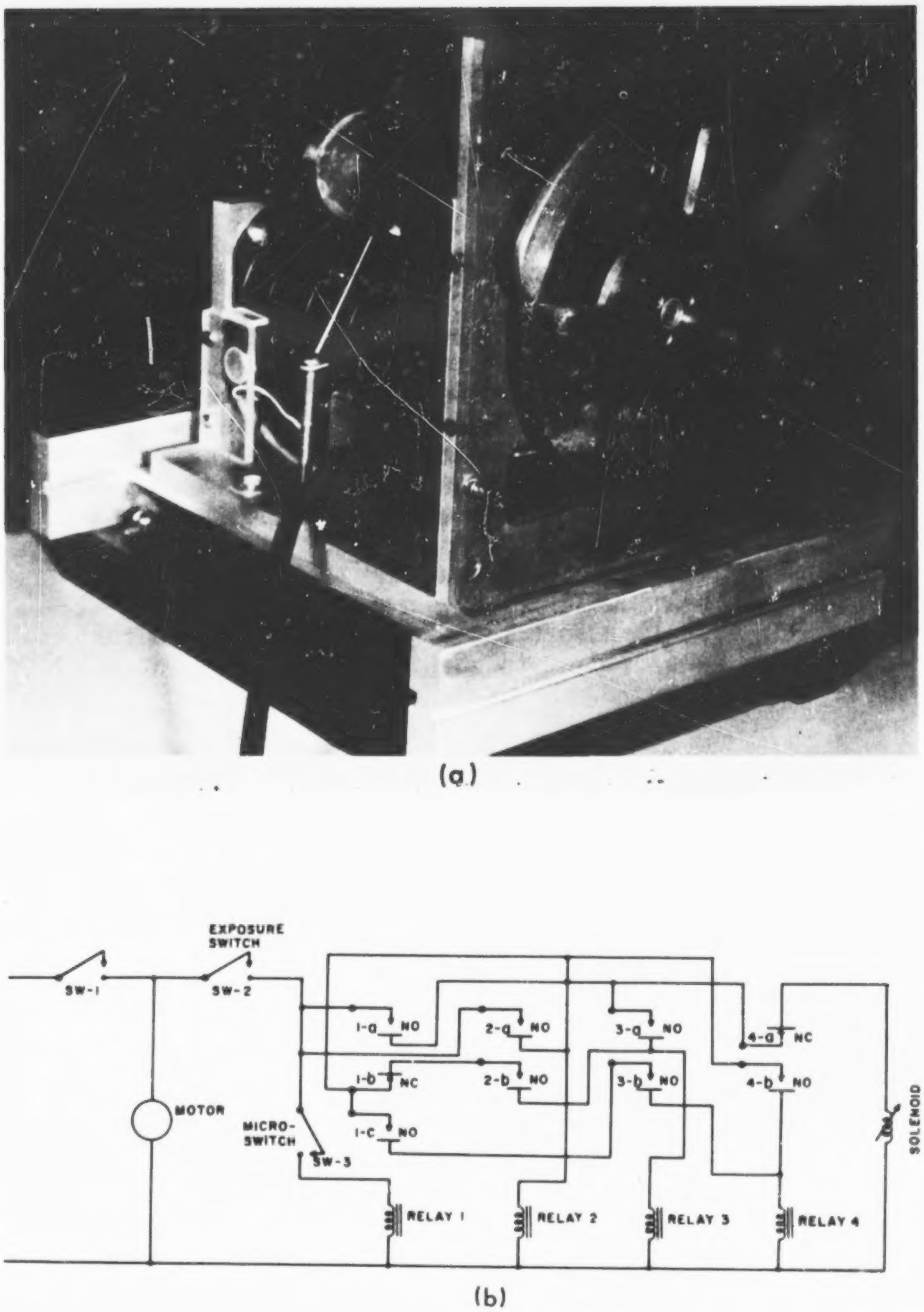

(a)
EXPOSURE SWITCH
SW-1
SW-2
1-a NO
2-a NO
3-a NO
4-a NC
1-b NC
2-b NO
3-b NO
4-b NO
MOTOR
MICRO-SWITCH
SW-3
1-c NO
SOLENOID
RELAY 1
RELAY 2
RELAY 3
RELAY 4
(b)

Figure 16. Photograph of timer – shutter mechanism and circuit diagram of the relay system.

OPTICAL BENCH

The optical bench with its associated apparatus is shown in figure 17.

With exposure rate from the x-ray tube and exposure time precisely controlled, gradated exposures to the imaging devices could be rapidly produced by moving the imaging device to predetermined positions along the optical bench and making an exposure at each of these positions. Calculations were made to determine those distances whose incremental difference would result in a 0.15-log unit change in exposure to the imaging device. In these calculations, variations because of both inverse square law and air absorption were taken into account. Air absorption coefficients published by the National Bureau of Standards were used (11). Air absorption corrections were not large, nor was the variation of air absorption with beam qualities between 2-mm Al and 6-mm Al half-value-layers; therefore the distances calculated for a 4-mm Al beam were used at the 3 half-value-layers at which exposures were made.

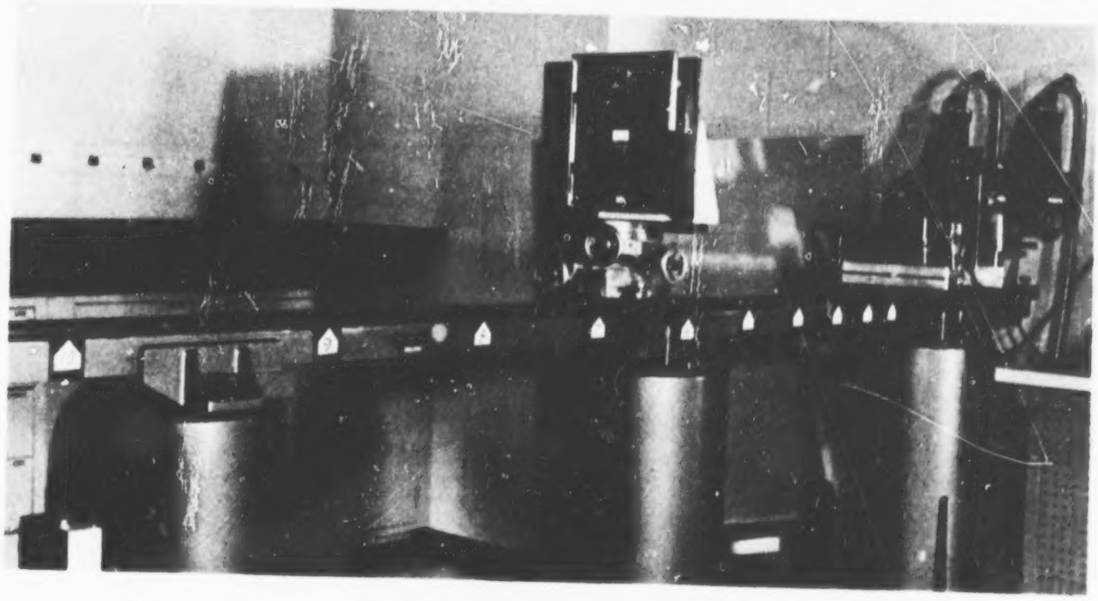


Figure 17. Photograph of optical bench showing x-ray tube, stabilizer ion chamber, and timer — shutter mechanism at the right; cassette and lead shield on an optical bench rider near the center of the bench. The large numbers on the bench are the distance numbers described in the text.

Calculations were checked by direct measurements, and the results are shown in figure 18. In this figure, the distance numbers are those which were assigned to the various positions on the optical bench. It will be seen that there is a detectable but minor difference between the points for the 2-mm Al beam and the 4-mm Al beam at the greater distances. This was neglected in the calculations of the film properties. The actual exposure rate difference between steps was 0.145-log unit rather than the 0.15 originally calculated. This was taken into account in determining film properties.

The optical bench rider, cassette holder, and lead shield are shown in figure 17. The manner in which the device was used is described in chapter III, under the heading "General Procedures."

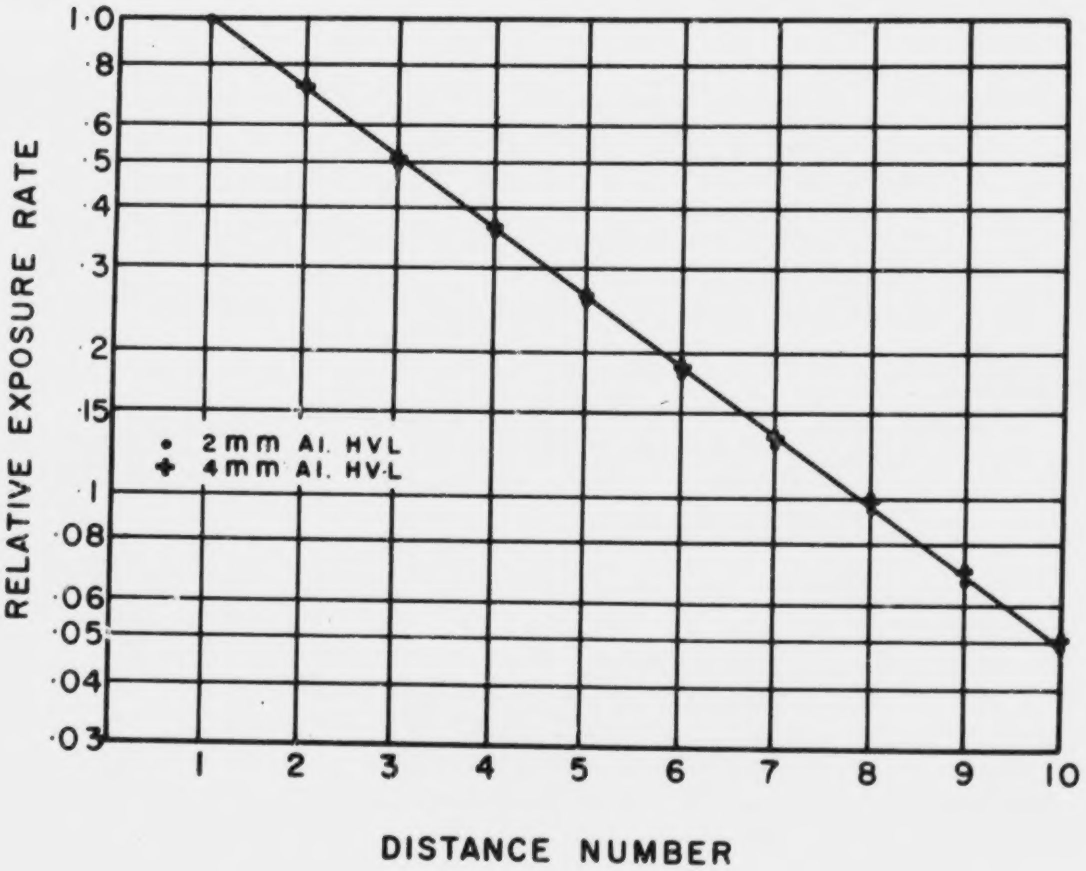


Figure 18. Variation of exposure rate with assigned distances along the optical bench.

Calibration of the Exposure System

The output of the operational amplifier was proportional to the exposure rate from the x-ray tube over a satisfactory range of beam qualities, and the digital voltmeter (used to measure this output voltage) served as a monitor of the exposure rate. The variation of exposure rate along the optical bench was determined as explained above. The exposure rate per volt swing of the digital voltmeter was measured at one distance on the optical bench. From this value, the digital voltmeter reading during a series of exposures, and the data presented in figure 18, the exposure rate at any other position on the optical bench could be rapidly calculated.

For example, with a beam of 4-mm Al half-value-layer, the exposure rate at distance number 1 on the optical bench was found to be 3.17×10^{-3} R/sec/volt. A representative voltage swing for exposures made at this beam quality was 15.36 volts. Hence, the exposure rate at this point on the optical bench was 4.87×10^{-2} R/sec. With a 0.1-second exposure time, the exposure would be 4.87×10^{-3} R. If it were found from the H and D curve that density $D = 1$ occurred at distance number 4.2, the data in figure 18 shows that the exposure at this distance was 0.32 of that at distance number 1.0. Therefore, the exposure to produce $D = 1$ is $4.87 \times 10^{-3} \times 0.32 = 1.56 \times 10^{-3}$ R, and the speed: $1/(1.56 \times 10^{-3}) = 6.4 \times 10^{2}$ R^{-1}. To facilitate these calculations, H and D curves were plotted as density versus distance number.

The sensitivity of the ionization chamber used on the exposure-rate stabilizer was sufficiently dependent on beam quality that calibrations were necessary at the 3 half-value-layers used in the experiments.

The free-air chamber described in the previous chapter had not been developed to the point where it could be considered a standard instrument; therefore, the final calibrations of the exposure system were made with a Victoreen R-meter, which had been calibrated by the National Bureau of Standards over the range of half-value-layers used in the experiments. The calibration of this instrument by the National Bureau of Standards was claimed to have an accuracy of ± 2 percent. The precision with which the exposures were controlled was well within this range.

CHAPTER VI. THE DARKROOM SYSTEM

GENERAL DESIGN

The apparatus used to process the film samples is shown in figure 19. Figure 19-a is a general view of the apparatus. A large rectangular tank constructed of stainless steel and insulated on six sides held 60 gallons of water. The temperature variation of the water was restricted to about ± 0.05° F. This water served as the temperature control bath for the solutions used in the development and fixing process. Processing solutions were contained in four 1½-gallon stainless steel tanks set in the bath through holes cut in the top of the large tank. These smaller tanks were provided with covers to prevent inadvertent contamination of solutions, and

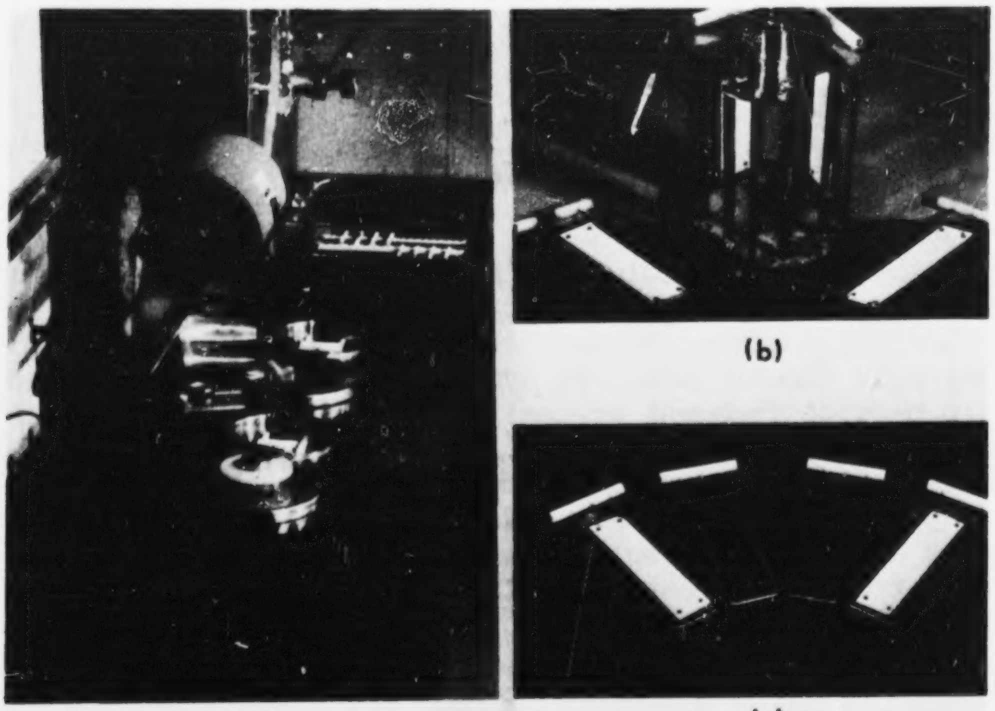

(a) (b) (c)

Figure 19. Apparatus used to process film samples.

the covers were thermally insulated to permit better temperature control. Three of these tanks contained the developer in use, stop bath, and fixer. A fourth contained fresh developer that would be used the following day. The tank containing the developer in current use was provided with an agitator (figure 19-b) and is described in more detail below.

The type of film hanger used is shown in figure 19-c with film samples in place. The hanger was constructed to carry a 6- by 1½-inch piece of film. The film was fastened to the hanger through the use of four hooks which engaged two holes punched in each end of the film sample. A small spring provided adequate tension to hold the film in place. Film samples were cut to size and the holes were punched prior to the x-ray exposure of the film.

Since developer, stop bath, and fixer were set in the temperature control bath, these three solutions were at similar temperatures. This avoided any possibility of emulsion reticulation. Films were washed in a tank separate from the temperature control bath this is shown in the upper right corner of figure 19-a. The wash water was continuously changed and its temperature was maintained near that of the other solutions by means of a Fotogard Powers thermostatic control valve. Films were dried by rapidly moving air in an anhydrous drier, but not at an excessively high temperature.

FILM AGITATION

If the developer solution is not kept in motion relative to the film, developer in contact with the emulsion will become chemically exhausted and development will proceed at an increasingly slower rate. To avoid this, various methods are used to provide frequent or continuous exchange of the developer at the surface of the film. The general term applied to these methods is "agitation."

One commonly used method is to introduce nitrogen gas at the bottom of the developer tank. As bubbles rise to the surface they cause circulation of the developer. The nitrogen does not react chemically with the developer or with the film emulsion. A second method is to have a series of paddles sweep back and forth through the developer near the surface of the film. Of these two methods, the paddle system is probably more practical, and, for large film samples (8 by 10 inches, or greater) is probably the method of choice. Since the film samples to be used in these measurements were relatively small, it was considered that better agitation could be accomplished by a third method — motion of the film samples rather than the developer.

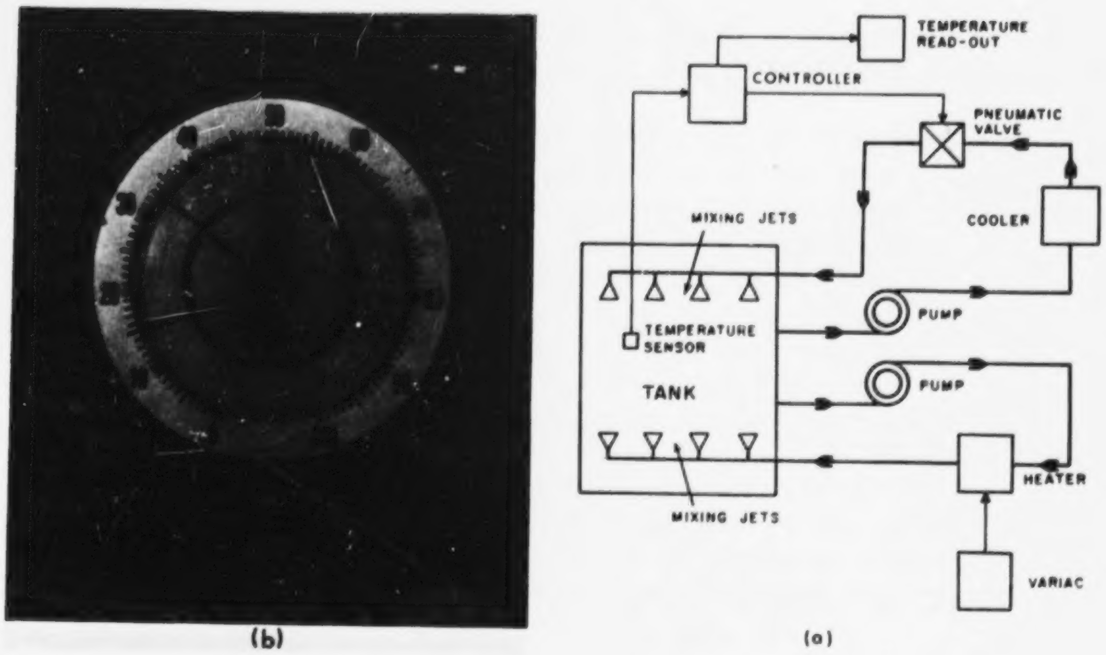
The device used to provide agitation is shown in figure 19-b. Slots on the periphery of a cylindrical cage were provided to hold four film hangers. The cage was mounted on a Teflon bearing that was fixed to the center of a circular plate at the bottom of the developer tank. This bearing permitted the cage to rotate about the axis of the cylinder. An extension from the top of the cage engaged a shaft that passed through the cover of the developer tank. The second bearing for the rotary motion was provided by a Teflon insert in the cover. On the end of the shaft which was external to the cover, an eccentrically mounted pin could be coupled to a reciprocating arm by engaging the pin in a hole drilled in the arm. This arm, powered by an electric motor, oscillated the cage through an angle of 90° with a frequency of 30 cycles per minute.

When films were to be processed the cage was submerged in the developer solution. Films fastened to the film hangers were dropped in the slots and the cover was placed over the tank so that the shaft engaged the cage extension. The reciprocating arm was attached to the eccentric pin and the motor was turned on. All these motions were performed in a few seconds. The procedure to remove the films required even less time.

For development times as short as 1 minute, agitation was carried out for better than 80 percent of the development time. The reciprocating action was vigorous enough that this loss of agitation time did not significantly affect the measurements.

TEMPERATURE CONTROL

A major source of error in measurements that involve processed film is the variation of developer temperature; therefore, provision was made to control temperature within narrow limits. Feedback principles were used in this control system. The temperature control system was designed in cooperation with the Minneapolis-Honeywell Corporation, from whom the electronic and pneumatic components were purchased. A block diagram of the system is shown in figure 20-a. The tank shown in this figure is the temperature control bath.



(b) (a)

Figure 20. Schematic diagram of temperature control system and temperature readout showing 24-hour variation of temperature. Full scale is 1° F.

Water from the bath was pumped through two separate circulation loops. In one loop, the water flowed over a "calrod" electric heater which ensured a continual flow of heat into the system. This was necessary when developer temperature was to be maintained above ambient temperature and ensured a more rapid response of the control system when developer temperatures were maintained at or near ambient temperature. The rate of heat input was controlled through the manual adjustment of a "variac" which controlled electric power to the heater.

The automatic control of the bath temperature was effected through the second circulation loop. In this loop, water was pumped through a cooler, then through a pneumatically operated valve, and back to the temperature control bath. The rate of flow of cold water was controlled by the valve that opened or closed an amount proportional to an error signal transmitted through the electronic controller from the temperature sensor in the bath.

To ensure thorough mixing, water from both loops was forced back into the bath through manifolds containing several high-velocity nozzles.

A readout that displayed temperature variations in the bath was provided in the form of a meter and a circular chart recorder. Figure 20-b shows this readout. The meter and recorder gave full-scale deflection for a 1° F. change in temperature. The tracing on the chart is the variation in temperature that occurred over a 24-hour period. This variation had a range of about ± 0.05° F. The temperature at which the control system operated could be varied through the interchange of precision resistors in the controller circuit.

The temperature of the developer was measured with a precision thermometer that could be read to 0.1° C. Developer temperatures were measured before and after the transfer of a normal number of films into and out of the developer, and before and after the agitator was operated for times comparable to normal operation. No variation in developer temperature could be detected.

CHAPTER VII. DATA ANALYSIS

MEASUREMENT ERRORS

SOURCES OF ERROR

The factors that contributed to the dispersion of the measurements may be divided into three categories: (1) those associated with the apparatus comprising the laboratory system, (2) human error, and (3) those associated with variations within the samples received from the commercial companies. While deviations arising from this last category are not errors in the true sense of the word, they are referred to as errors to simplify discussion. The overall dispersion (or error of the measurements) was considerably greater than would be expected in view of the precise control exerted by the laboratory system. All known sources or error are mentioned here so that the deviations of the results may be viewed in their proper perspective. The most sensitive indicator of error is film speed and the following discussion is oriented toward errors in the measurement of this property.

The sources of error associated with the apparatus were:

1. Variation of exposure rate.
2. Variation of beam quality.
3. Variation of exposure time.
4. Variation of developer temperature.
5. Lack of adequate agitation during development.
6. Densitometer error.

These factors would probably contribute an overall error of ± 1 percent to the speed measurements. This error is almost entirely associated with the densitometer. The precision of this instrument was 0.02 density units. A variation of 0.02 density units would result in about a 1-percent change in the speed determination of a film with a contrast factor of 3.0.

Sources of human error were:

1. Deviation of the imaging device from its intended position during exposure.

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2. Variation in procedures used to mix each batch of developer.
3. Variation in development time.
4. Errors in densitometer readings.
5. Errors in plotting graphs.
6. Errors in taking values from graphs.
7. Errors in calculations.

The procedures associated with exposure and development were carried out as carefully as possible and as repetitively as possible. The H and D curves were plotted by one person and checked by a second from recorded values of the densities. All calculations were carried out by one person and repeated independently by a second. When differences in results appeared, the source of miscalculation was found before the differences were considered resolved.

It is difficult to estimate the magnitude of error introduced by these factors. It was likely of the order of 1 or 2 percent; therefore an estimate of 1.5 percent was made.

The "errors" contributed by variations within the samples under evaluation were:

1. Variation in light emission per unit exposure from different areas of the intensifying screen.
2. Variations in sensitivity of different areas of the film emulsion.
3. Variations in individual packages of the developers used in the experiments.
4. Variations in light intensity per unit exposure produced by changes in screen temperature.
5. Variations in sensitivity of the emulsions because of changes in moisture content of the emulsion.
6. Variations in sensitivity of the emulsions because of changes in emulsion temperature.

The first three of these sources could not be controlled during the measurements. The only control exerted on the last three sources was that provided by the air-conditioning system of the building.

No attempt was made to evaluate the contribution directly of each of the above factors to the overall dispersion of the measurements. One or two experiments were performed to ensure that the variations were due predominantly to normal variations in the samples provided and not to errors associated with the laboratory system or procedures. These are described in the two following subsections.

TYPICAL H AND D CURVE

Figure 21 shows an H and D curve for a medium-speed film used with a medium-speed screen. The curve is drawn through the average of the densities obtained with five samples of the film type. The samples were exposed and developed under identical conditions but were neither exposed nor developed simultaneously. The range of densities obtained is shown on the graph. This range could be considered typical in the sense that it is roughly the average variation found; in general, the variation increased with the speed of the film, but it was also different for different film types having similar speeds. The range of densities shown in figure 21 would result in a 2.7-percent range of speed measurements.

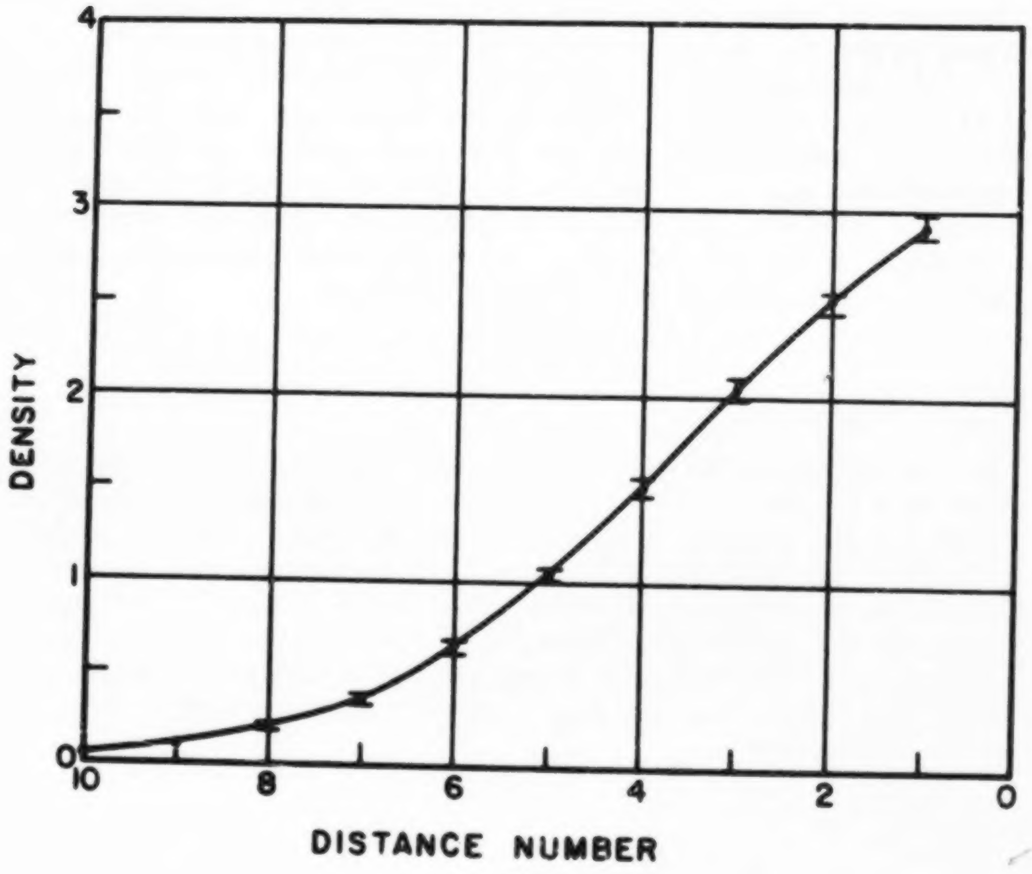

Figure 21. Typical H and D curve obtained with laboratory system. Ranges of five film samples are shown on curve.

When samples were exposed or developed simultaneously, there was no observable reduction in the density variations; therefore, it was concluded that exposure control, control of development temperature, degree of agitation, and the precision of the darkroom procedures were adequate.

CONTINUITY CHECK

The day-to-day variation of the measurements was checked as follows. A large number of samples of one film type were given identical exposures in one day and set aside to check the continuity of procedures. Two of these were developed each day the darkroom was used; one prior to the daily film load, a second after all other film had been processed. The speed measurements made from these films had a standard deviation of 4 percent for the several months over which this procedure was carried out.

Several of these films were split in two. One-half was developed prior to the film load, the second one-half afterwards. The standard deviation of the "before and after" speeds was well below 1 percent. This again indicated that in any one day the variation because of the darkroom system or development procedures was very small. In view of previous checks on the exposure system, the standard deviation of speed measurements brought about by variation in individual developer packages and developer mixes was about 3 percent.

SUMMARY

As far as could be determined, the laboratory system and the procedures used in the laboratory contributed less than 2 percent to the overall dispersion of the measurements. Variations within an emulsion type and a screen type over a series of exposures, together with variations in the final developer mix, were of the order of 4 percent. The overall deviations of the measurements, brought about by all sources of error listed at the beginning of this chapter, were probably not more than ± 5 percent.

SPEEDS OF FILM – SCREEN COMBINATIONS

A cursory review of the speed data taken at 1 half-value-layer indicated that the ratio of speeds obtained with any two screens was relatively independent of the film with which they were used, and similarly that the ratio of the speeds obtained with any two films was independent of the screen with which they were used. These relationships between films and screens are physically possible if two conditions are met:

1. The contribution to the speed of the film – screen combination by the direct action of x rays on the film is negligible; or alternatively, this contribution for different films is very nearly identical.
2. The spectral emission of all screens and the spectral response of all films are such that a spectral match or mismatch would provide no particular advantage or disadvantage in the use of a particular film – screen combination.

If these conditions were met, the relative speeds of screens could be obtained through measurements with one film type and the relative speeds of films could be obtained through measurements with one screen type. From these measurements the speeds of all film – screen combinations could be calculated.

That the first condition was adequately met was verified by subsequent measurements of the speed of screen-type film used without intensifying screens. The average contribution to the speed of film – screen combinations by the direct action of x rays on screen-type film is 3.8 percent when films are used with the slowest available screen. The range of this contribution with various films is from 3.3 to 4.8 percent. When used with a medium-speed screen, the contribution decreases to about 1 percent.

The second condition specified is likely to exist since calcium tungstate, which had a characteristic light emission in the blue portion of the spectrum, is apparently the fluorescent material used in all intensifying screens, and the response of x-ray film emulsion is presumably maximum to blue light. This could not be verified directly in the laboratory; therefore the procedures used in the analysis of variance (12) were carried out to determine whether or not the second condition was met.

Since the ratios of the speeds for one film with various screens and the ratio of the speeds for one screen with various films were to be examined, the analysis was made on the logarithms of the speeds. Table 3 shows the results of this analysis for each half-value-layer.

Since the root-mean-square of the interactions between films and screens was within the estimated error of the measurements for all three qualities of radiation, it was assumed that the conditions specified above did exist. Accordingly, future measurements of the speed of film – screen combinations could be markedly simplified.

Table 3. Analysis of variance of logarithms of film — screen combination speeds for 2-, 4-, and 6-mm Al data

Source	Degree of freedom	Sum of squares		
		2-mm Al	4-mm Al	6-mm Al
Total	220	8.9297	11.1357	12.7490
Screens	16	4.7102	6.6282	7.9020
Films	12	4.1739	4.4728	4.8183
Interactions	192	0.0456	0.0347	0.0287
Mean square of interactions		0.000237	0.000181	0.000150
Root-mean-square of interactions		0.0154	0.0135	0.0122
Relative variation		0.035	0.030	0.029

The relative error decreased with increasing half-value-layer. This is possible because the measurements at 2-, 4-, and 6-mm Al were made in that chronological order and the precision with which the procedures were carried out increased as more experience was gained; however, the dependence of speed on beam quality decreases as half-value-layer increases, and variations in beam quality probably contributed to the deviations to a greater degree at the lower half-value-layers.

SPEEDS OF NONSCREEN FILMS

The number of measurements on these photoreceptors were relatively few. Their speeds showed little dependence on beam quality and were not subject to variations in intensifying screens. As a result, these data were considerably more consistent than those for the film — screen combinations.

VARIATION OF SPEED WITH HALF-VALUE-LAYER

The total light exposure to a film exposed with intensifying screens is given by

$$E_1 = kE\ (1 + \mu a)\ (1 + f) \qquad (16)$$

where

- k is the efficiency of the front screen in terms of light emission per unit x-ray exposure,
- E is the x-ray exposure,
- μ is the fractional transmission of the front screen,
- a is the sensitivity of the rear screen relative to the front screen, and
- f is the fractional light transmission of the undeveloped film.

If f were constant or very small for each film type, then any change in speed brought about by a change in beam quality would be governed by the screen only. Densitometry with blue light indicated that f was of the order of 0.15 and varied less than ± 0.01 with the film types under evaluation. It was assumed that there were no other factors which would make the variation of speed on half-value-layer interdependent of film type. The following analysis was carried out to check the above relationship and possibly provide a method to "smooth" the speed measurements.

For a given screen, the log average of the speed of all films with that screen was calculated at 2-, 4-, and 6-mm Al. This yielded a reference line for the variation of speed with half-value-layer for that screen. Figure 22 shows this reference line for a medium-speed screen. The ratios of the measured speeds of a film to this reference line was then calculated at the 3 half-value-layers and the average of these ratios taken. It was then assumed that this average expressed the ratio of the film speed to the reference line at all half-value-layers. This was then repeated for all films used with that screen. The results of these calculations are shown in figure 22 for two films. The entire procedure was then repeated for each screen.

The standard deviation of the measured values from those obtained by the above smoothing procedure was 5.3 percent. This value is very nearly the cumulative error that would result from the relative errors determined for each half-value-layer through the analysis of variance procedures described earlier. These results reinforced the assumption that there were no factors involved in the variation of speed with half-value-layer other than those specified in equation 16.

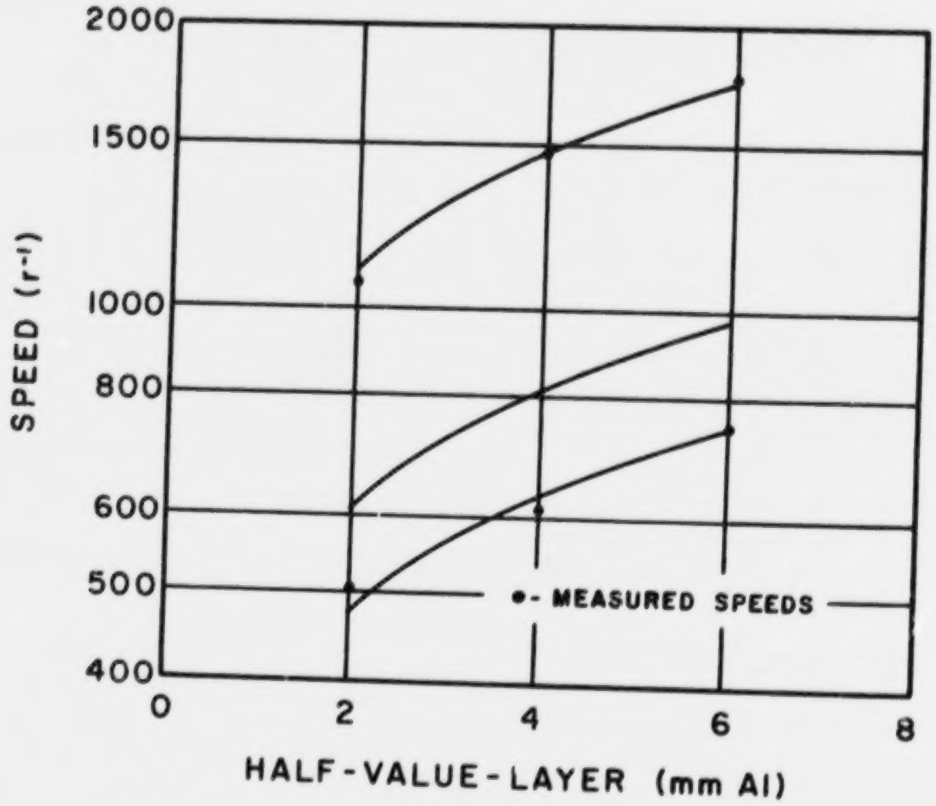

Figure 22. Graph demonstrating method used to "smooth" speed measurements.

On these grounds it was assumed that the values taken from the graphs were more probably correct than the original measurements. The smoothed values were those presented.

REPEATED SPEED MEASUREMENTS

The speed measurements of all film — screen combinations at 3 half-value-layers were repeated with an abbreviated procedure as indicated in the list of experiments in chapter III. The overall results of these measurements are shown in table 4 where the percentage change of the repeated measurements from the original measurements are given. The percentages are the average for each film used with all screens at all half-value-layers. Column 3 gives the results when the repeat measurements were made with films from the original sample supplied by the manufacturer. The values in Column 4 are the results when films from a second sample supplied by the manufacturer were used in the repeat measurements. These latter samples were supplied about 1 year after the initial

Table 4. Results of repeated speed measurements on all film-screen combinations. The percentage changes shown are the average changes from original to repeated measurements for the film listed when used with all screens and at all half-value-layers

Company	Film type	Percentage change same emulsion batch	Percentage change different emulsion batch
A	1	--	- 8
	2	+ 4	
	3	+ 8	
B	1	- 1	-13
	2	- 3	
C	1	- 7	
	2	- 2	
	3	- 1	
D	1	-16	
	2	-16	
E	1	- 8	
	2	- 8	
F	1	- 1	-10

samples and were undoubtedly produced from a different emulsion batch. The variation with emulsion batch is not unexpected.

The repeated measurements were made about 1 year after initial measurements had begun. The films of companies D and E showed some decrease in speed from the original measurement. Because this reduction is constant for each company, and because the films from each company were not exposed and developed simultaneously, the decreases in speed were presumed to be real and not an experimental error.

The variation with emulsion batch and the variation with storage time will probably be the subject of future experiments.

The remaining films demonstrated good agreement with the original measurements.

CONTRAST FACTOR

Each screen was assigned an integral number from 1 to 17, and graphs of contrast factor versus these numbers were plotted for all films. Figure 23 shows the graphs obtained with two film types. Each graph consisted of three sets of points, one for each half-value-layer. These graphs showed no clear correlation between contrast factor and half-value-layer, nor did any particular screen show a consistently high or low contrast factor with all films.

The average contrast factor for each film used with all screens was calculated and the standard deviation of these values from the average was determined. The standard deviation for each film type ranged from 3 to 7 percent. The

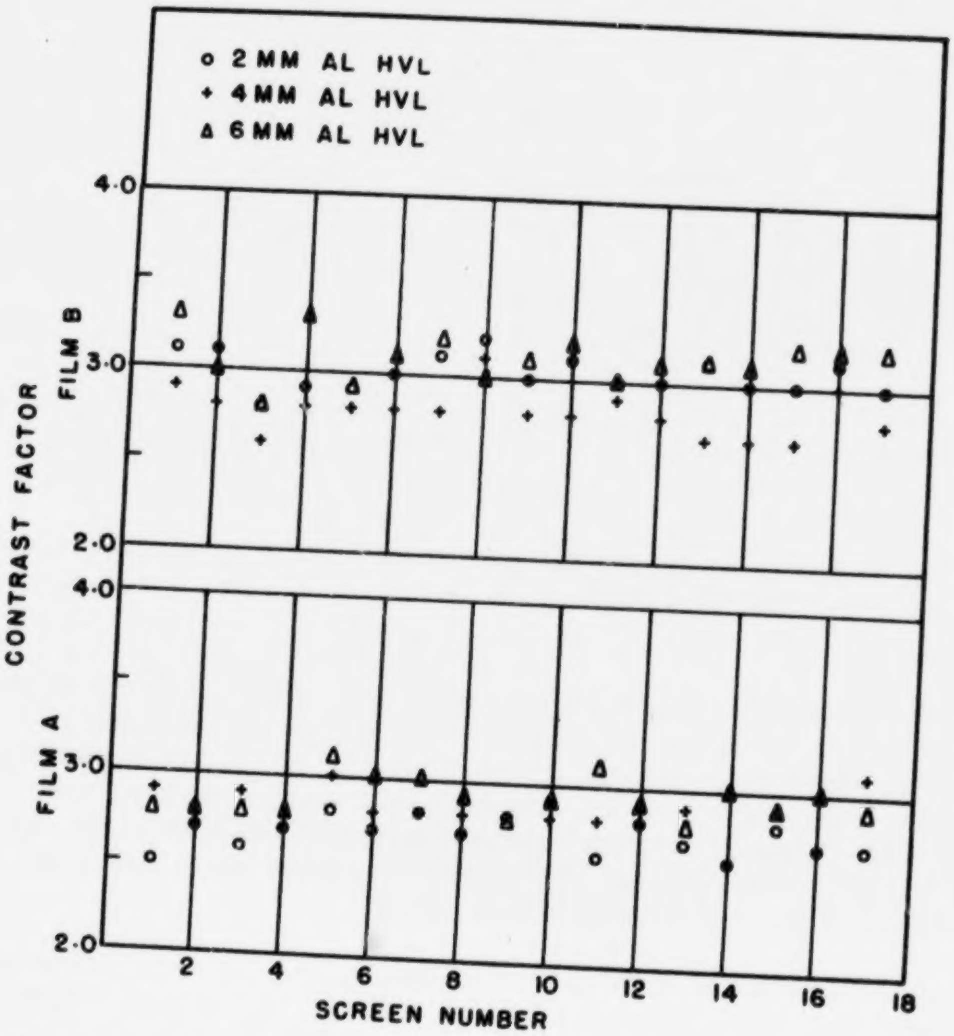

Figure 23. Contrast factor versus arbitrarily assigned screen numbers. Data are given for two film types. For each film type values at 3 half-value-layers are shown.

standard deviation of the entire set of measurements was 5.3 percent. It was concluded that within the limits of experimental error, contrast factor was determined by the film only and was not modified by the screen with which the film was used or by the half-value-layer of the x-ray beam.

LATITUDE

An identical procedure was carried out in the analysis of the latitude measurements. The conclusion regarding latitude was identical with that of contrast factor — that it was a property of the imaging device determined by the film only. The dispersion of the measurements about the average was less for latitude than for contrast factor. This probably reflected the additional error introduced in the contrast factor measurements when tangents to the H and D curves were determined graphically.

BASE AND CHEMICAL FOG DENSITY

The value of the base density of the various film types was noted periodically throughout the experiments. There was no change. Chemical fog was plotted against storage time of the film. This plot showed the expected increase with storage time.

RECIPROCITY LAW FAILURE

The speeds of the various films were plotted against exposure time to determine the exposure time at which the films would exhibit maximum speed. The variation of speed with exposure time is discussed in chapter VIII.

LATENT IMAGE FADING

The speeds of the various films were plotted against the time interval between exposure and development. Some films showed an increase in speed (a latent image enhancement rather than a fading of the latent image). No reference to this effect had been noted in the literature; therefore, these experiments were repeated to check the possibility of an experimental error. The results are discussed in chapter VIII.

VARIATION OF PROPERTIES WITH DEVELOPMENT CONDITIONS

The analysis of this phase of the experiments consisted essentially of plotting speeds, contrast factor, latitude, and fog density for all films against developer temperature and development time for the various developers used. The interrelationships considered significant are demonstrated by the choice of graphs included in the appendix. The graphs, together with the table of speeds, represent the format in which the data will be published.

CHAPTER VIII. SUMMARY AND CONCLUSIONS

As indicated previously the entire body of data from the measurements will not be presented here because of its bulk; instead, a brief summary of the properties of films and film — screen combinations available to radiologists and conclusions drawn from the data regarding the factors that influence these properties will be presented.

SPEEDS

The distribution of the speeds of film — screen combinations when these devices are exposed at a beam quality of 4-mm Al half-value-layer, and when the films are developed for 3 minutes in Kodak Liquid Developer at 20° C. range from slightly over 200 R^{-1} to about 2,700 R^{-1}. The most frequent speed is 800 to 900 R^{-1}. This also represents the speed of the film — screen combinations most frequently used in general diagnostic radiology.

The speed of a screen relative to any other screen is independent of the film with which it is used. Similarly, the speed of a film relative to any other film is independent of the screen with which it is used.

The variation of the speed of a film — screen combination with half-value-layer is a function of the screen only and not of the film with which it is used. Fast screens display a greater change in speed with half-value-layer than do slow screens. A change from 2- to 6-mm Al increased the speed of the fastest available screen by a factor of 1.8, the slowest by a factor of 1.3.

The speed of the five nonscreen films ranged from 25 to 50 R^{-1}. The speeds of these films are relatively independent of half-value-layer, increasing by only 10 percent when the half-value-layer increases from 2- to 6-mm Al.

Screen-type films when exposed without screens have speeds in the range of 6 to 22 R^{-1}. They show even less dependence on half-value-layer than do nonscreen films.

Speeds vary with the type of developer in which the films are processed. The advantage in speed obtained with a particular developer must be considered with regard to the fog density which results from that developer.

Speeds may be increased by increasing development time and/or developer temperature. These two factors also bring about changes in contrast factor and fog density; hence these properties must also be considered when a choice of development conditions is made. Fog density usually sets an upper limit to the speed that may be obtained through the increase of development time or development temperature.

CONTRAST FACTOR

Contrast factors for screen-type films range from 2.6 to 3.3 and for nonscreen films from 1.4 to 2.2; in general, contrast factors are higher for the higher speed films but there are one or two notable exceptions. The highest contrast factor found was provided by a medium-speed film.

Contrast factor is governed by the film only, is independent of the screen with which it is used, and is independent of the half-value-layer of the x-ray beam.

Contrast factor increases with development time and development temperature up to the point where the film is adequately developed; that is, where the speed tends to increase very slowly with development time and fog density begins to increase markedly. Beyond this stage of development, contrast factor remains constant until development time or temperature are increased to an excessive degree. At this point contrast factor begins to decrease. Contrast factors remained constant when films were processed in the various manual developers used in the experiments; in general, the contrast factors obtained with automatic developers were less than those obtained with manual developers.

LATITUDE

The latitudes of screen-type films ranged from 0.45 to 0.60, and of nonscreen film from 0.8 to 0.9. As would be expected from the definitions, any variation in contrast factor is accompanied by an inverse variation of latitude, but this is not always a proportionate variation. In general, all factors that affect contrast factor can be considered to bring about a comparable inverse variation in latitude.

FOG DENSITY

The initial fog density measurements of the films ranged from 0.03 to 0.11. These measurements were made relatively soon after the films were received from the supplier and may be considered representative values. At the end of 9 months' storage at room temperature in an air-conditioned building, fog densities had doubled for all films.

Fog density changes slightly with development time in the range of times recommended by the developer manufacturer. Beyond these times it shows a marked increase with development time. It is also critically dependent on developer temperature. A change in temperature of a manual developer from 20° C. to 25° C. will increase fog density by a factor of 2.5 with a 4-minute development time. Films with comparable speeds may differ considerably in the fog densities they exhibit.

BASE DENSITY

Base densities of the different film types ranged from 0.06 to 0.09. Because the precision of the densitometer was ± 0.02 density units, base densities are, for practical purposes, equal for all films.

RECIPROCITY LAW FAILURE

The graphs of film speed versus exposure time exhibited a broad maximum over a wide range of exposure times for all films. The speed variation for exposure times between 0.01 second and 0.1 second was less than ± 5 percent of the average speed over this time range. All screen-type films exhibited a loss of speed at exposure times of 1 second and 10 seconds. Currently available films exhibit their maximum speeds at those exposure times most frequently used in diagnostic radiography.

LATENT IMAGE EFFECTS

Repeat measurements of latent image fading confirmed the original findings that the speed of several films did in fact increase over a certain time interval between exposure and development; in general, the speed of these films increased for the first 24 hours, then decreased over the following 6-hour period.

Insofar as normal radiologic procedure is concerned, this increase in speed is of academic interest only. The reduction in patient exposure that could be effected by delaying the development of the film is so small (about 10 percent), that it is far outweighed by the possible disadvantage of a delay in the acquisition of diagnostic information.

Similarly, latent image fading over the normal time interval between the exposure of a radiograph and its development is not very important from the point of view of patient exposure or image quality.

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APPENDIX

The following tables and graphs are a sample of the format in which the data will be published. Data are to be presented under the heading of each film type because most of the factors which affect the characteristics of photoreceptors exert their influence on the film.

Table 1 and graphs 1 through 9 are the data which will be presented for each screen-type film. Data for nonscreen films will be that shown in table 2 and graphs 1 through 8. Graph 9, which shows reciprocity effects is, of course, not applicable to nonscreen film.

Table 1. Speed (R^{-1}) with various screens at half-value-layers shown

Manufacturer:

U.S. Distributer:

Base Density: 0.08 Contrast: 2.7 Latitude: 0.58

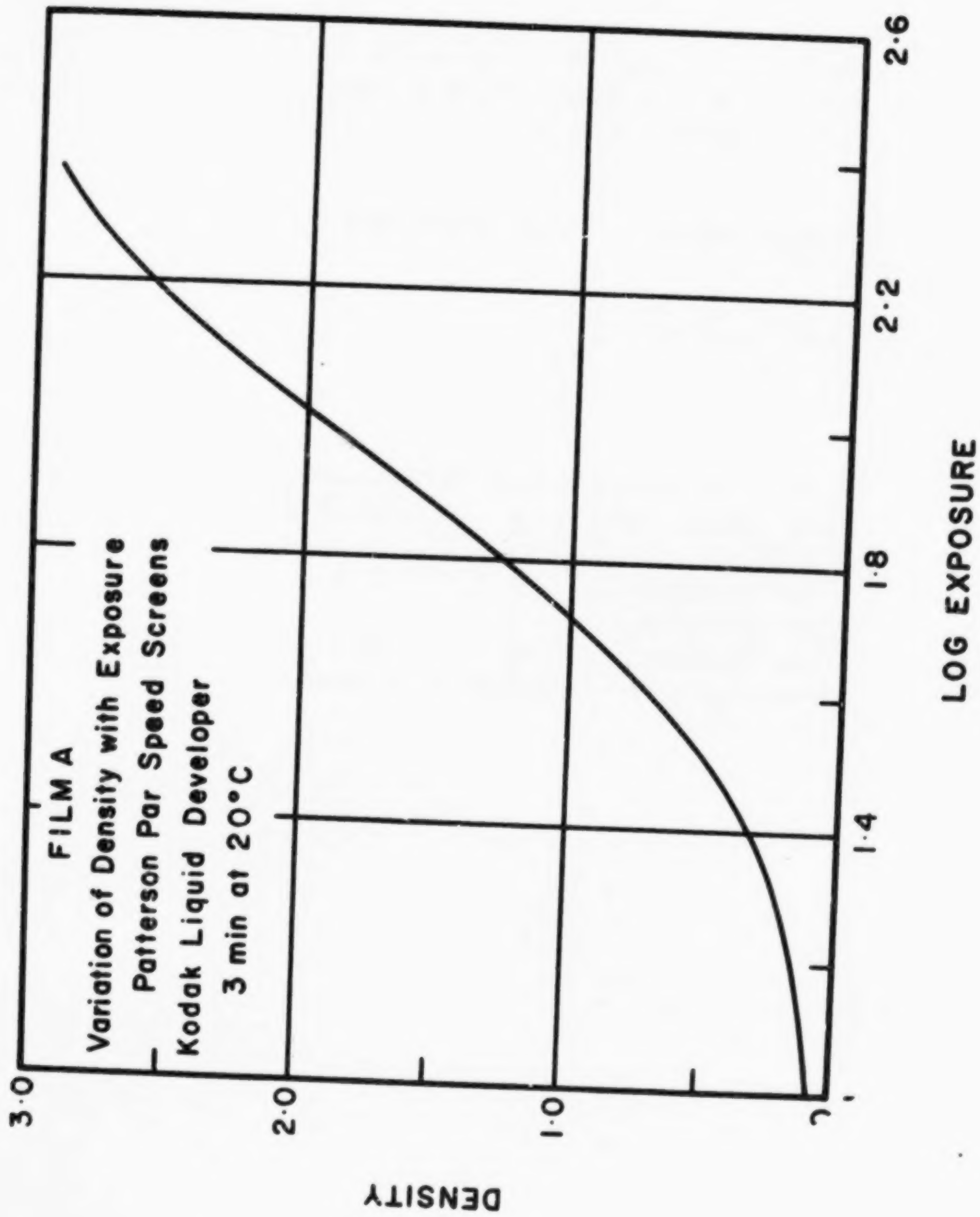
Screen	Half-value-layer		
	2-mm Al	4-mm Al	6-mm Al
Ansco Medium Speed	700	950	1110
Ansco High Speed	730	1160	1470
Auer Flash-Speed	900	1390	1740
Buck A	600	840	980
Buck AA	750	1060	1260
Buck AAA	750	1170	1460
Ilford Standard	580	810	970
Ilford Fast	1060	1560	1900
Patterson Detail	400	530	590
Patterson Par-Speed	680	880	1010
Patterson Hi-Speed	820	1310	1700
Radelin UD	280	350	400
Radelin HR	360	440	490
Radelin T	630	840	1000
Radelin TF	960	1390	1720
Wolf Rapid	680	930	1110
Wolf Ultra	730	1070	1320
Without Screens	11	12	12

Table 2. Speed (R^{-1}) at half-value-layers shown — Film B (non-screen film)

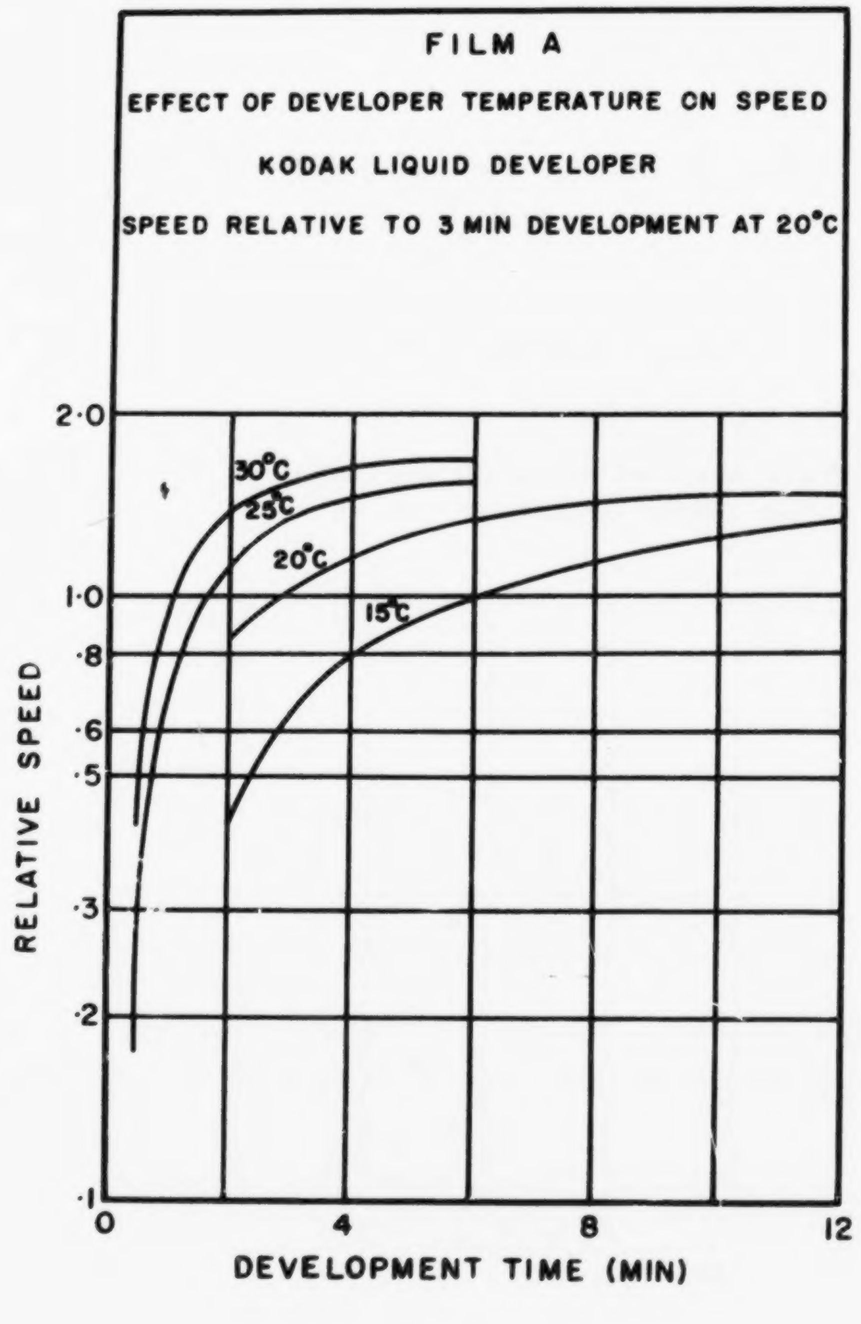
Manufacturer: U.S. Distributer:

Base Density: 0.07
Contrast: 1.90
Latitude: 0.86

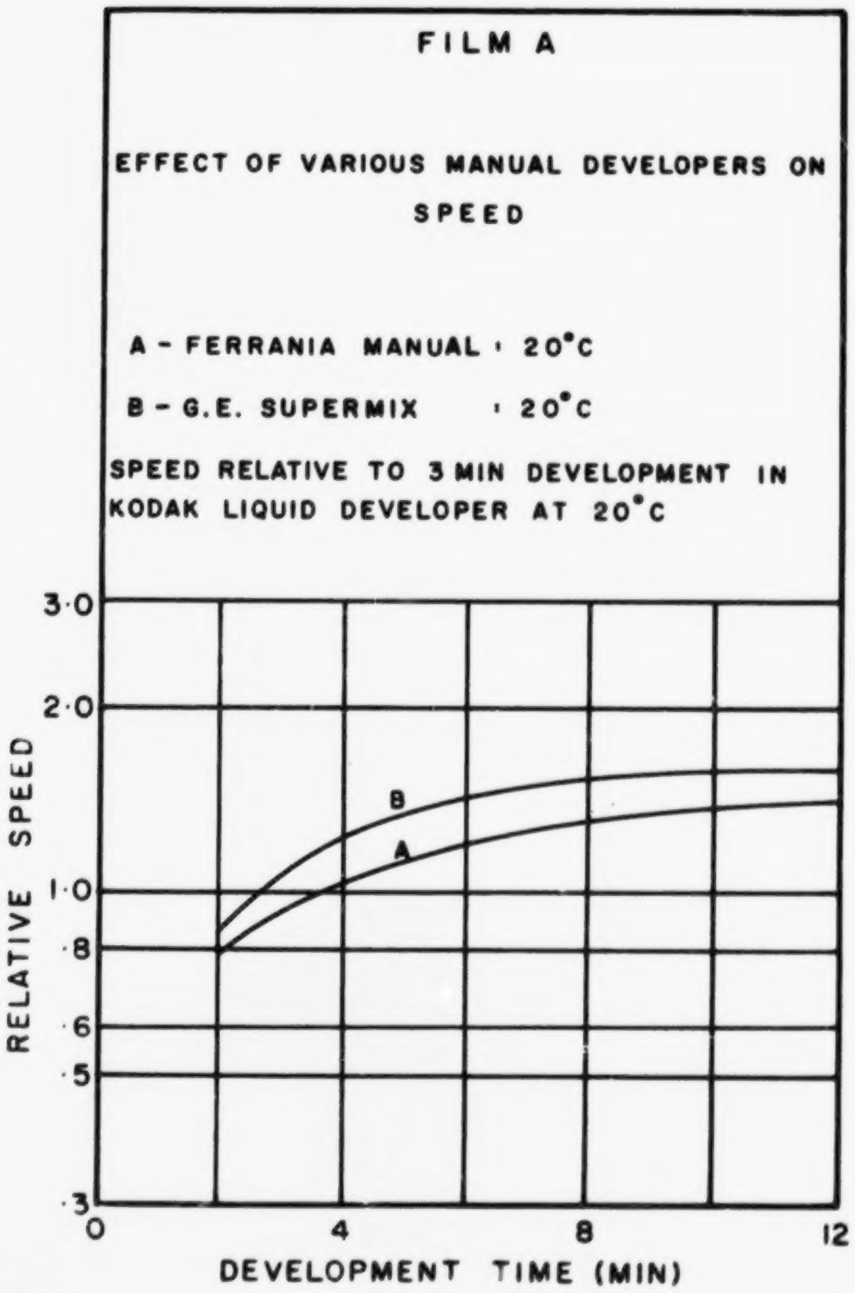
Half-value-layer	Speed (R^{-1})
2-mm Aluminum	20.6
4-mm Aluminum	25.3
6-mm Aluminum	26.1


FILM A
Variation of Density with Exposure
Patterson Par Speed Screens
Kodak Liquid Developer
3 min at 20°C
DENSITY
3·0
2·0
1·0
0
LOG EXPOSURE
1·4
1·8
2·2
2·6

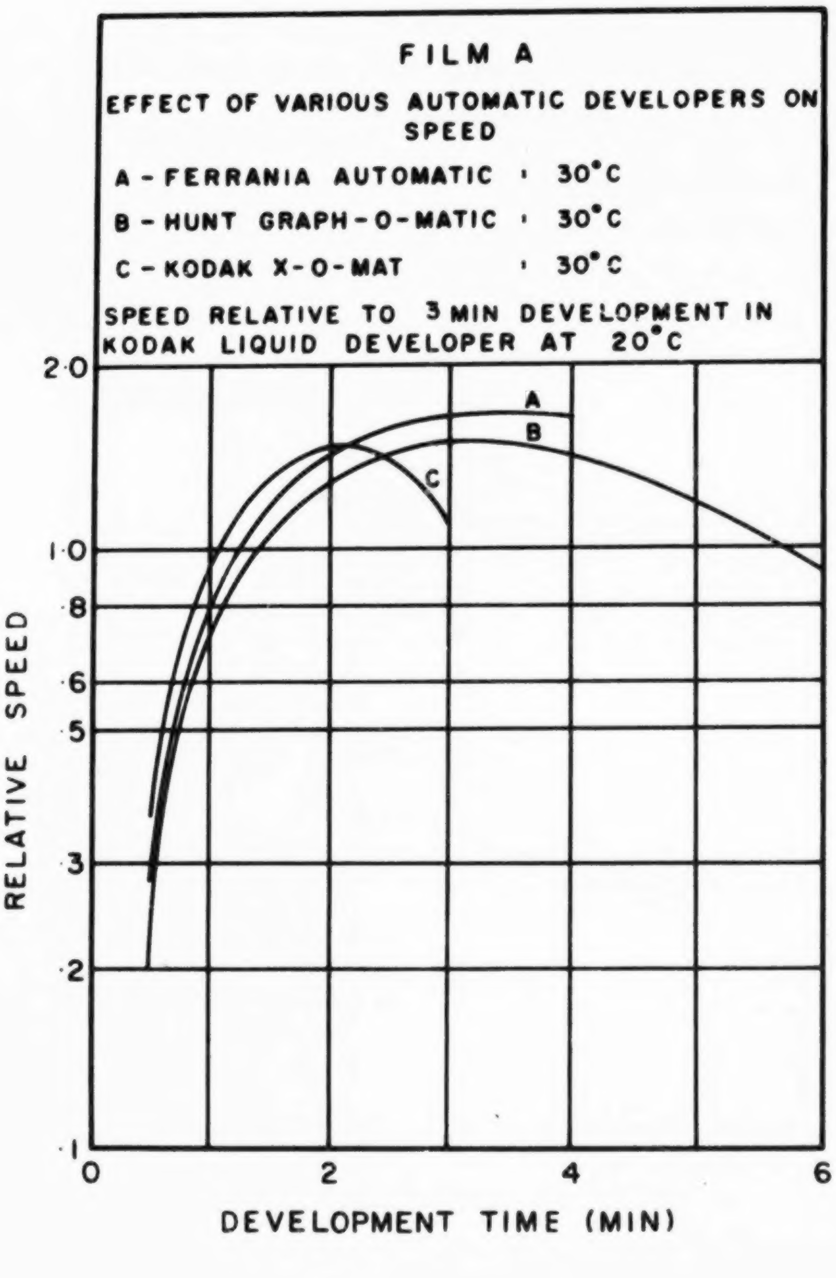
Graph 1


FILM A
EFFECT OF DEVELOPER TEMPERATURE ON SPEED
KODAK LIQUID DEVELOPER
SPEED RELATIVE TO 3 MIN DEVELOPMENT AT 20°C
2·0
1·0
·8
·6
·5
·3
·2
·1
RELATIVE SPEED
0
4
8
12
DEVELOPMENT TIME (MIN)
30°C
25°C
20°C
15°C

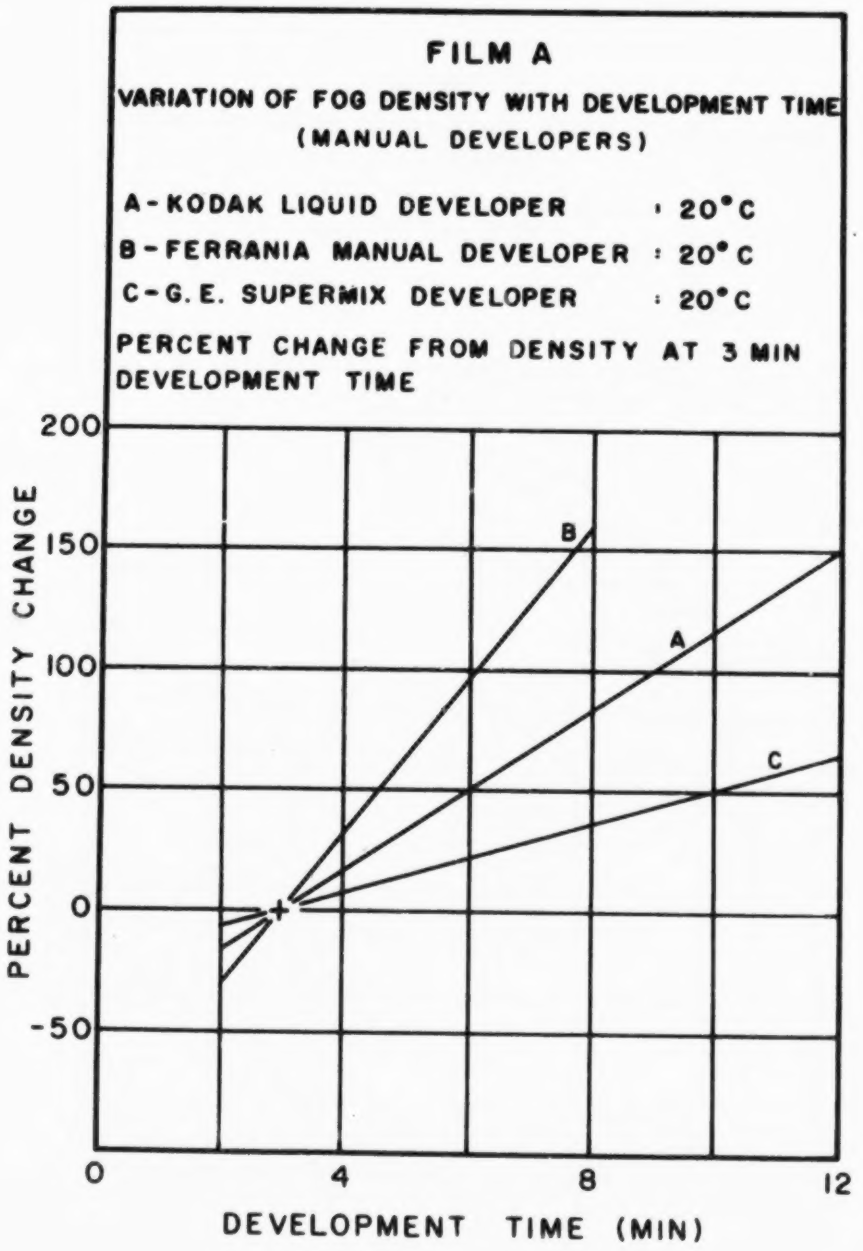
Graph 2


FILM A
EFFECT OF VARIOUS MANUAL DEVELOPERS ON SPEED
A - FERRANIA MANUAL : 20°C
B - G.E. SUPERMIX : 20°C
SPEED RELATIVE TO 3 MIN DEVELOPMENT IN KODAK LIQUID DEVELOPER AT 20°C
3·0
2·0
1·0
·8
·6
·5
·3
RELATIVE SPEED
B
A
0
4
8
12
DEVELOPMENT TIME (MIN)

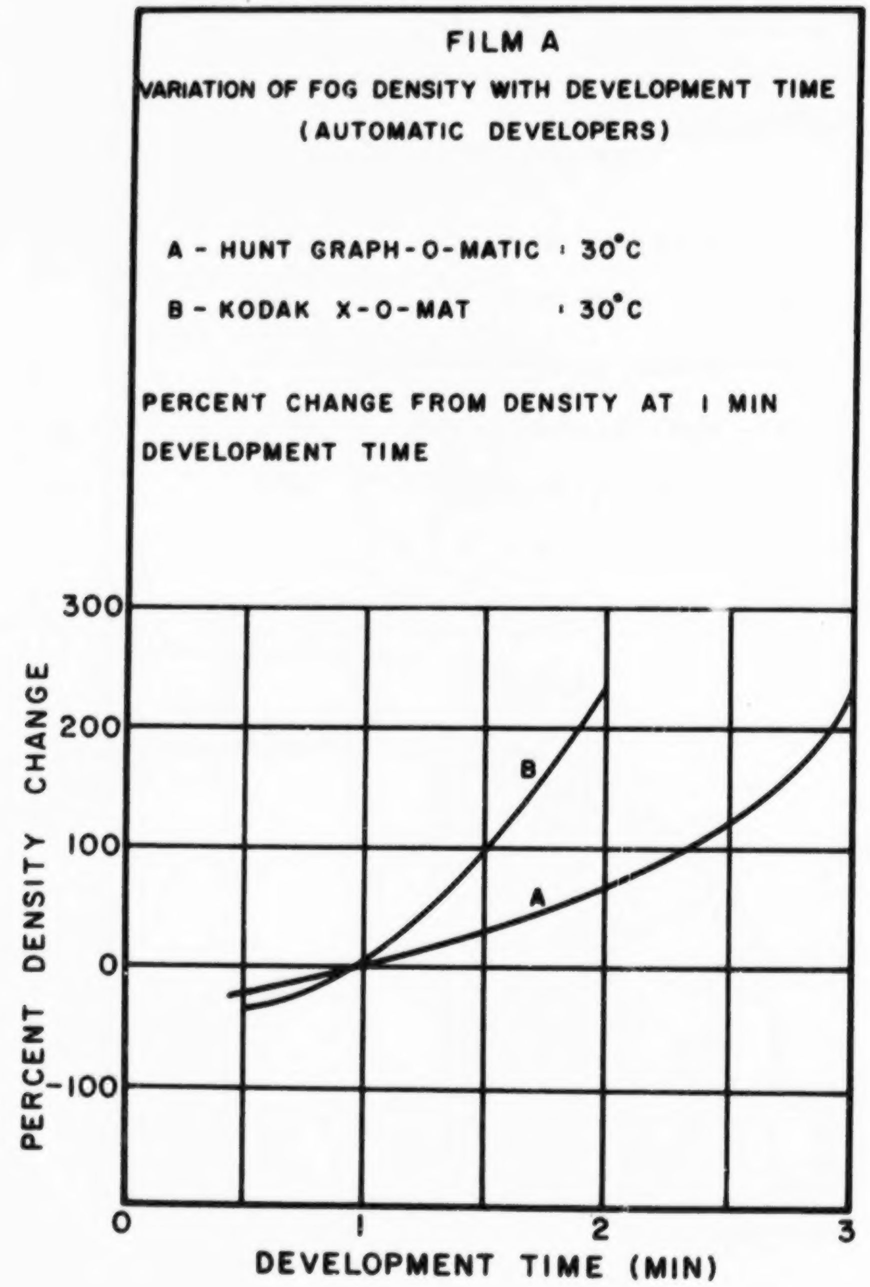
Graph 3


FILM A
EFFECT OF VARIOUS AUTOMATIC DEVELOPERS ON SPEED
A - FERRANIA AUTOMATIC : 30°C
B - HUNT GRAPH-O-MATIC : 30°C
C - KODAK X-O-MAT : 30°C
SPEED RELATIVE TO 3 MIN DEVELOPMENT IN KODAK LIQUID DEVELOPER AT 20°C
A
B
C
2·0
1·0
·8
·6
·5
·3
·2
·1
RELATIVE SPEED
0
2
4
6
DEVELOPMENT TIME (MIN)

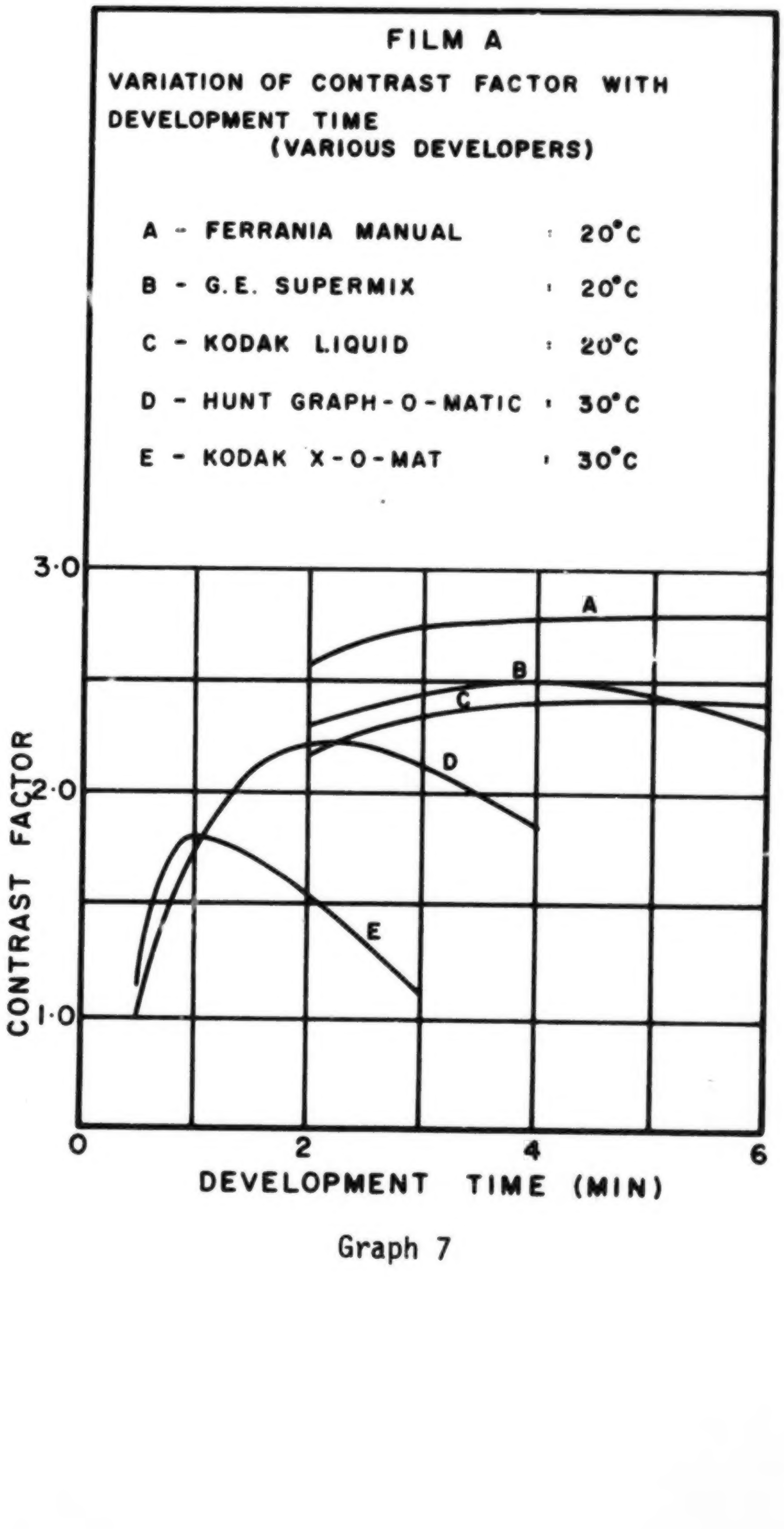
Graph 4


FILM A
VARIATION OF FOG DENSITY WITH DEVELOPMENT TIME
(MANUAL DEVELOPERS)
A - KODAK LIQUID DEVELOPER : 20°C
B - FERRANIA MANUAL DEVELOPER : 20°C
C - G. E. SUPERMIX DEVELOPER : 20°C
PERCENT CHANGE FROM DENSITY AT 3 MIN DEVELOPMENT TIME
PERCENT DENSITY CHANGE
200
150
100
50
0
-50
B
A
C
0
4
8
12
DEVELOPMENT TIME (MIN)

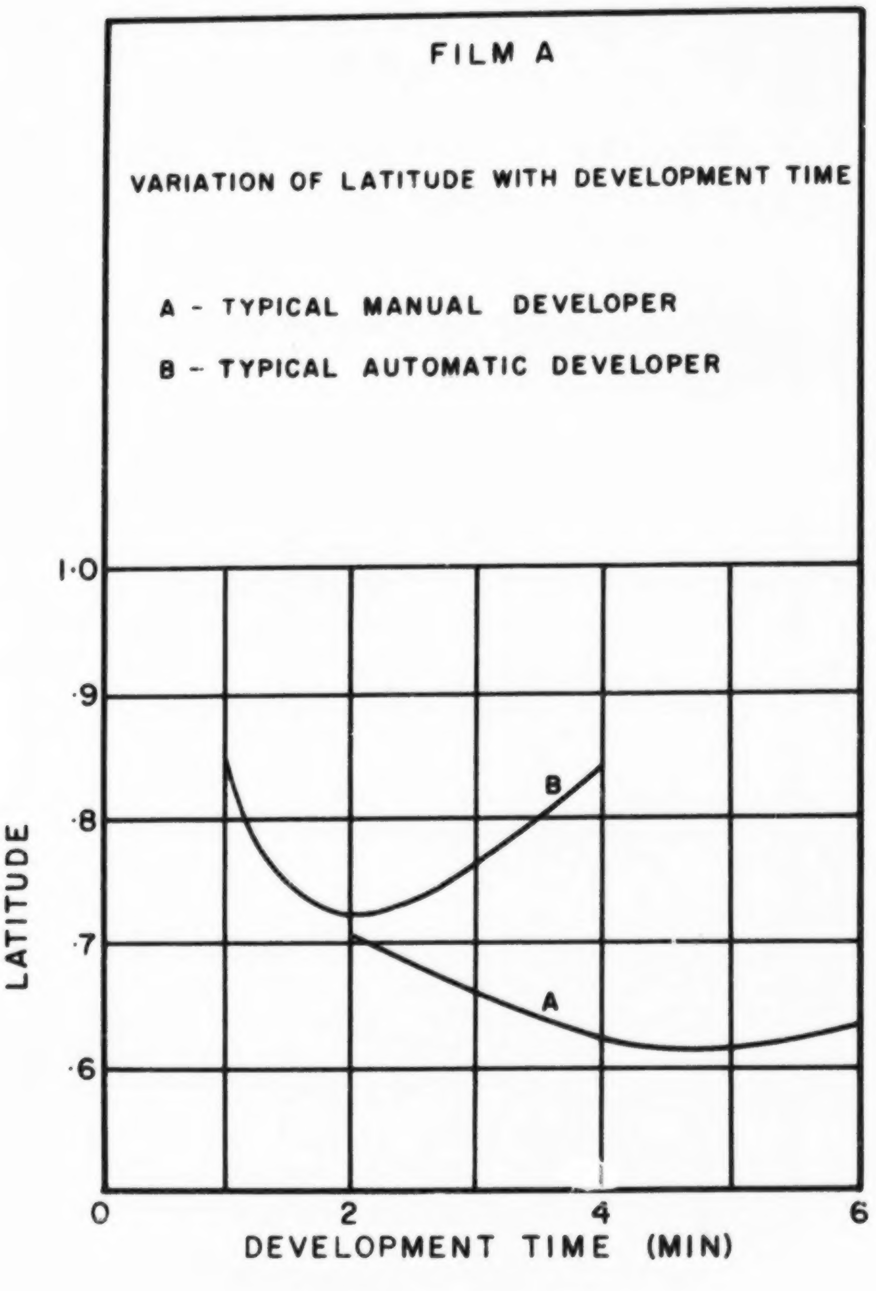
Graph 5


FILM A
VARIATION OF FOG DENSITY WITH DEVELOPMENT TIME
(AUTOMATIC DEVELOPERS)
A - HUNT GRAPH-O-MATIC : 30°C
B - KODAK X-O-MAT : 30°C
PERCENT CHANGE FROM DENSITY AT 1 MIN DEVELOPMENT TIME
PERCENT DENSITY CHANGE
300
200
100
0
-100
0
1
2
3
DEVELOPMENT TIME (MIN)
A
B

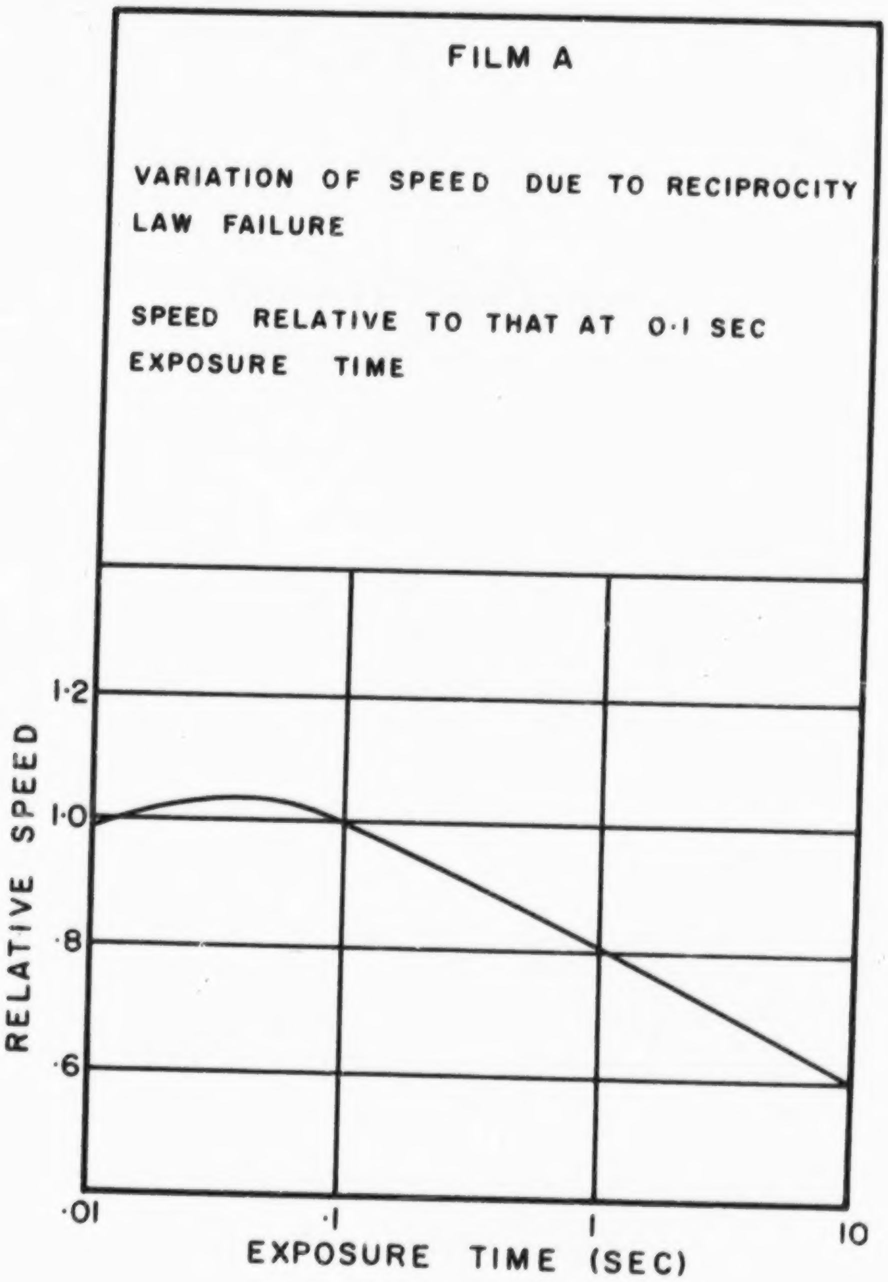
Graph 6


FILM A
VARIATION OF CONTRAST FACTOR WITH DEVELOPMENT TIME
(VARIOUS DEVELOPERS)
A - FERRANIA MANUAL : 20°C
B - G.E. SUPERMIX : 20°C
C - KODAK LIQUID : 20°C
D - HUNT GRAPH-O-MATIC : 30°C
E - KODAK X-O-MAT : 30°C
3·0
2·0
1·0
CONTRAST FACTOR
0
2
4
6
DEVELOPMENT TIME (MIN)
A
B
C
D
E

Graph 7


FILM A
VARIATION OF LATITUDE WITH DEVELOPMENT TIME
A - TYPICAL MANUAL DEVELOPER
B - TYPICAL AUTOMATIC DEVELOPER
1·0
·9
·8
·7
·6
LATITUDE
0
2
4
6
DEVELOPMENT TIME (MIN)
B
A

Graph 8


FILM A
VARIATION OF SPEED DUE TO RECIPROCITY LAW FAILURE
SPEED RELATIVE TO THAT AT 0·1 SEC EXPOSURE TIME
RELATIVE SPEED
1·2
1·0
·8
·6
·01
·1
1
10
EXPOSURE TIME (SEC)

Graph 9

ENVIRONMENTAL HEALTH SERIES

RADIOLOGICAL HEALTH

The following technical reports issued by the Bureau of Radiological Health are available through the Office of Public Information and Education, Bureau of Radiological Health, Public Health Service, U.S. Department of Health, Education, and Welfare, Rockville, Md. 20852.

PHS Pub. No.	Title
999-R-1	Factors Influencing Strontium-90 in Milk from Brainerd, Minn. Milkshed
999-R-2	Rapid Methods for Estimating Fission Product Concentrations in Milk
999-R-3	Studies of the Fate of Certain Radionuclides in Estuarine and Other Aquatic Environments
999-R-4	Mathematical Programming Models for Selection of Diets to Minimize Weighted Radionuclide Intake
999-R-5	Radionuclide Analysis of Gamma-Ray Spectra by Stepwise Multiple Regression
999-R-6	Farming Practices and Concentrations of Fission Products in Milk
999-RH-7	An Environmental Surveillance Laboratory for Radionuclide Analyses
999-RH-8	X-Ray Equipment Survey in Polk County, Florida — September 1961-August 1963
999-RH-9	An Emanation System for Determining Small Quantities of Radium-226
999-RH-10	Procedures for Determination of Stable Elements and Radionuclides in Environmental Samples
999-RH-11	Radiochemical Determination of Uranium in Environmental Media by Electrodeposition
999-RH-12	Radioactive Decay Correction Factors
999-RH-13	Behavior of Certain Radionuclides Released into Fresh-Water Environments — Annual Report 1959-1960
999-RH-14	Iodine-131 in Children's Thyroids from Environmental Exposure
999-RH-15	Quality Control of Radioactivity — Counting Systems
999-RH-16	Medical Uses of Radium and Radium Substitutes
999-RH-17	Radionuclide Analysis of Large Numbers of Food and Water Samples
999-RH-18	Mortality of New England Dentists 1921-1960
999-RH-19	Soil and Sediment Analysis: Preparation of Samples for Environmental Radiation Surveillance
999-RH-20	Standards of Performance for Film Badge Services
999-RH-21	A Computer Program for the Analysis of Gamma-Ray Spectra by the Method of Least Squares
999-RH-22	Scientific Information Retrieval System for Research Grants
999-RH-23	Routine Surveillance of Radioactivity Around Nuclear Facilities
999-RH-24	Distribution of Cobalt 60, Zinc 65, Strontium 85, and Cesium 137 in a Freshwater Pond
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999-RH-27	Radioassay Procedures for Environmental Samples
999-RH-28	Full Scale System for Removal of Radiostrontium from Milk
999-RH-29	Tritium Contamination in Particle Accelerator Operation
999-RH-30	Reduction of Radiation Exposure in Nuclear Medicine
999-RH-31	An Acclimation Room for the Detection of Low Radium 226 Body Burdens
999-RH-32	Common Laboratory Instruments for Measurement of Radioactivity
999-RH-33	Guidelines to Radiological Health
999-RH-34	Georgia Radium Management Project
999-RH-35	Regulations, Standards, and Guides for Microwaves, Ultraviolet Radiation, and Radiation from Lasers and Television Receivers — An Annotated Bibliography
999-RH-36	Evaluation of Radium Contamination in Aircraft Instrument Repair Facilities
999-RH-37	Regulations, Standards, and Guides Pertaining to Medical and Dental Radiation Protection — An Annotated Bibliography

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BATES, LLOYD M: Some physical factors affecting radiographic image quality: their theoretical basis and measurement.

U.S. Department of Health, Education, and Welfare, Public Health Service Publication No. 999-RH-38 (August 1969) 101 pp. (limited distribution).

ABSTRACT. This project carried out under contract between The Johns Hopkins University and the Bureau of Radiological Health, Public Health Service, reviews the medical diagnostic process involved in determining the pathological condition of a patient made on the basis of available roentgenological information. In diagnostic roentgenology, information relating to the patient is made available through the medium of x rays and is displayed in the form of a visual image. The final step in information acquisition is the detection and recognition by the roentgenologist of patterns in the image.

Several years ago, a program of work on the physics of diagnostic roentgenology was established at The Johns Hopkins University. The general purpose of this program was threefold: (1) to carry out a fundamental study of the parameters of an imaging system that affect image quality; (2) to devise methods to measure these parameters; and (3) to make

(over)

ACCESSION NO.

KEYWORDS:

Contrast
Density
Exposure
Film
Filter
Fog density
Image quality
Imaging process
Latent image fading
Modulation transfer
Optics
Photoreceptor
Radiography
Reciprocity law failure
Resolution
Unsharpness
Visible image
X ray

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The manner in which the measurements were analyzed and a summary of the characteristics of radiographic films and screens currently available in the United States are included. Detailed data from the measurements are not included because of their bulk; these data will be published as a separate report in the Environmental Health Series. A set of tables and curves are presented in the appendix of this report to indicate the format in which the data will be published.

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